EPA 813-R-93-003

Ground Water Resource Assessment

U.S. Environmental Protection Agency
Office of Ground Water and
Drinking Water

October 1993

ACKNOWLEDGEMENTS

This document was prepared for the U.S. Environmental Protection Agency, Office of Water, Ground Water Protection Division. James Hamilton was the Work Assignment Manager for this project.

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The Ground Water Protection Division wishes to thank the technical committee members, without whom, this document could not have been produced.

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EXECUTIVE SUMMARY

This document is intended to provide guidance to State[1] resource managers who are conducting a ground water resource assessment. For the purposes of this document, EPA defines a resource assessment as:

(1) the collection, analysis, and presentation of existing and new data on:

- (a) geology and hydrogeology
- (b) ground water vulnerability
- (c) current and potential land use
- (d) current and potential aquifer use, *and*

(2) the use of these data in making ground water protection decisions.

Why Should States Conduct Resource Assessments?

EPA encourages each State to develop and implement a Comprehensive State Ground Water Protection Program (CSGWPP) that ties together its various efforts in ground water protection. EPA has identified six strategic activities that together make up an adequate and complete CSGWPP. The second strategic activity calls for establishing priorities based, in part, on a characterization of ground water resources.

Resource assessments provide the information managers need to conduct a variety of State and Federal ground water protection programs. The information produced from a resource assessment will enable managers to understand their ground water resources, identify existing and possible future problems, prioritize the problems for action, and act to resolve those problems.

[1] Includes States, Tribes, and local governments.

What is the Resource Assessment Process?

The resource assessment process as outlined by EPA begins with collecting and analyzing data on the physical ground water system, followed by a consideration of the ground water's use, value, and vulnerability to human activity. This process includes ten **Components** that characterize the physical and chemical properties of the resource. These Components are:

(1) <u>Regional Hydrogeologic Setting</u> -- Hydrogeologic factors that control the regional occurrence, movement, and availability of ground water: hydrogeology, topography, regional climate, hydrography, soil, vegetative cover, regional recharge and discharge patterns, ground water quality, geochemistry, and geophysical characteristics.

(2) <u>Aquifer and Aquifer-System Occurrence</u> -- Areal distribution and three-dimensional position of aquifers in the geologic sequence.

(3) <u>Water Table and Potentiometric Surface</u> -- Water table: the upper surface of the saturated portion of an unconfined aquifer. Potentiometric surface: water surface elevation to which water will rise in a well tapping a confined aquifer.

(4) <u>Hydraulic Properties</u> -- The properties of soil, rock, sediment, and other geologic materials that govern the movement of water into, through, and out of an aquifer.

(5) <u>Confinement and Interaction Between Aquifers</u> -- Ease with which leakage between aquifers can occur. The greater the confinement, the less the interaction.

(6) <u>Ground Water Recharge and Discharge Characterization</u> -- Where, and at what rate, aquifers are recharged by infiltrating precipitation and ground water is discharged to the land surface.

(7) <u>Ground Water and Surface Water Interaction</u> -- Where, and at what rate, water moves between an aquifer and a body of surface water.

(8) Ground Water Budget -- An accounting of all natural and anthropomorphic removals from, and additions to, the ground water reservoir.

(9) Chemical and Physical Characteristics of Aquifers and Overlying and Underlying Materials -- Materials that make up the aquifer and overlying unsaturated and underlying zones. These materials have chemical and physical characteristics that impact water quality and affect the fate and transport of contaminants.

(10) Ambient Ground Water Quality -- The quality of ground water at a baseline time selected by the decision-making agency. Ambient quality may be the natural quality of ground water or may be the quality as impacted by widespread historical contamination. (Some aquifers may be naturally unsuitable for a variety of uses, while others are unsuitable as a result of contamination.)

In addition, EPA identifies four **Approaches** to resource assessment that managers can use to analyze how human activity might affect ground water resources now and in the future. These four Approaches consider:

(1) Aquifer Sensitivity -- The relative ease with which a contaminant applied on or near the land surface can migrate to an aquifer of interest. An aquifer's sensitivity is a function of the intrinsic characteristics of the geologic materials in question and the overlying saturated and unsaturated materials. Aquifer sensitivity is independent of land use and contaminant characteristics.

(2) Aquifer Use -- Quantification of ground water withdrawal rates and identification of types of use. This information allows managers to determine future trends, to plan for changes, or to modify existing practices.

(3) Land Use -- Uses of land may affect ground water resources. The type of land cover, including vegetation and manmade alterations such as pavement, directly affect the runoff and infiltration of precipitation.

(4) Ground Water Vulnerability -- The relative ease with which a contaminant applied on or near the land surface can migrate to an aquifer under a given set of land use management practices, contaminant characteristics, and aquifer sensitivity conditions.

EPA presents these various Components and Approaches as a "menu" from which State resource managers can choose the elements that best fit their own needs and financial and human resources. Although EPA does not expect that all States will choose to use all fourteen Components and Approaches, this document presents the elements in a rational order, where one Component or Approach might rely on information collected under a previous one.

Many States have conducted some kind of assessment of ground water resources, and most States already have available much of the information needed to begin a ground water resource assessment. EPA encourages managers who conduct resource assessments to acquire as much existing data as possible before incurring the expense of producing new data. Managers should make an effort to contact State and Federal agencies, universities, and other potential sources of ground water data before beginning their own data collection program.

A resource assessment can and should be refined over time as more and better data become available and as ground water management needs change. The fundamental objective of this iterative assessment process is to provide a resource-based framework upon which managers can make informed decisions.

Organization of the Document

Chapter 1 of this document provides an overview of EPA's resource assessment concept and discusses how a resource assessment can be used in decision-making, how it can benefit the user, and what types of data and analyses it produces. Chapter 2 describes each of the ten Components of a resource assessment in detail. Chapter 3 describes each of the four Approaches. For each Component and Approach the discussion includes:

- a detailed definition
- the Component's/Approach's objective

- data needs
- methods for characterizing the Component/Approach
- presentation of data
- considerations
- references

CHAPTER 1:

Introduction to Ground Water Resource Assessment

Assessing the condition of ground water resources is an essential first step in developing effective programs to protect those resources. This document summarizes the general methods available for collecting and analyzing hydrogeologic data, for determining land and aquifer use, and for establishing the sensitivity and vulnerability of ground water supplies. Knowledge of these methods will assist State[2] and Federal resource managers in preparing a Comprehensive State Ground Water Protection Program (see below).

Many of the elements of a resource assessment are commonly found in other Federal regulatory and nonregulatory programs.[3] The resource assessment process will help resource managers to integrate the various management strategies used in these different programs and to set priorities for ground water protection. It also will allow managers to address both existing problems (e.g., site remediation) and pollution prevention (e.g., wellhead protection). The process described in this document focuses on tools for protecting ground water across a broad region rather than a specific site. EPA recognizes, however, that the resource assessment process could be used for site-specific characterizations as well.

The resource assessment process helps managers to make the best use of existing ground water data, to identify gaps in critical data, and to consider all sources of information and funding if new data collection is required. Ground water protection and management programs do not have to cost more to work better: Resource managers can significantly improve the economy and effectiveness of their programs by sharing information with other

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[2] Includes States, Tribes, and local governments.

[3] Examples are the Resource Conservation and Recovery Act (RCRA); the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA); the Toxic Substances Control Act (TSCA); the Comprehensive Environmental Response, Compensation and Recovery Act (CERCLA or "Superfund"); the Underground Storage Tank (UST) Program; the Wellhead Protection Program (WHPP); the Sole Source Aquifer (SSA) Program; and the Public Water Supply Supervision Program (PWSSP).

government programs and avoiding needless duplication. The resource assessment process encourages State and Federal regulatory and non-regulatory organizations to cooperate in collecting new data. This type of collaboration already is underway for several regionally important aquifers such as the Ogallala (Midwest/High Plains Area), Edwards (Texas), and Biscayne (Florida) aquifers.

Each State will have to determine the extent of its own resource assessment efforts and its priorities for ground water protection based on available financial, human, and technical resources. That is, a State should decide which Components and Approaches described in Chapters 2 and 3 will be undertaken, and which products it deems most critical to its protection and management efforts.

Definition of Ground Water Resource Assessment

For the purposes of this document, *ground water resource assessment* is defined as:

(1) the collection, analysis, and presentation of existing and new data on:

- geology and hydrogeology
- ground water vulnerability
- current and potential land use
- current and potential aquifer use, *and*

(2) the use of these data in making ground water protection decisions.

This document does not discuss the assessment of ground water for ecological purposes. EPA plans to prepare a technical assistance document providing guidance to States on methods for delineating areas of ground water and surface water interaction. That document will discuss the impacts of the ground water and surface water interaction (hyporheic) zone on ecosystems.

Comprehensive State Ground Water Protection Program

In Protecting the Nation's Ground Water: EPA's Strategy for the 1990s (USEPA, 1991), EPA stated its policy to promote the development and implementation of a Comprehensive

State Ground Water Protection Program (CSGWPP) by each State. Resource assessments are at the center of comprehensive State programs because of they are an important first step in setting protection priorities. By encouraging the States in this initiative, EPA:

(1) recognizes that States have the primary responsibility for protecting their ground water resources

(2) focuses on resource protection as the principal (but not the only) basis for setting priorities across Federal, State, and Tribal ground water programs

(3) integrates Federal, State, and Tribal ground water program functions to more effectively and efficiently protect ground water resources

(4) recognizes its commitment to the concept of comprehensive resource protection in Federal ground water programs

EPA's National Guidance for CSGWPP (USEPA, 1992a) identifies six strategic activities of a comprehensive State program. These activities are as follows:

(1) *Establishing the State's ground water protection goal* to guide all relevant Federal, State and local programs operating within the State

(2) *Establishing priorities* for meeting that goal, based on characterization of the resource, programmatic needs, and identification of existing and potential sources of contamination

(3) *Defining authorities, roles, responsibilities, resources, and coordinating mechanisms* across relevant Federal, State, Tribal, and local programs

(4) *Implementing the actions necessary to accomplish the State's ground water protection goal*, consistent with the State's priorities and schedules

(5) *Coordinating information collection* to measure progress, re-evaluate priorities, and support all ground water-related programs

(6) *Improving public education and participation* in all aspects of ground water protection

The need for a resource assessment is addressed in the second strategic activity, "Establishing priorities," which encourages States to set ground water protection priorities based, in part, on a characterization of the ground water resource. This document will help with that characterization.

Existing Resource Assessments

Many States have already made significant progress toward a Statewide resource assessment. The Wisconsin and Ohio State Geological Surveys, for example, have produced aquifer yield maps, while the Illinois State Geological Survey has prepared Statewide maps of both aquifer sensitivity and vulnerability. Data on ground water resources can be obtained from many sources, including State geological surveys, departments of agriculture, regulatory and water resource agencies, universities, and regulated entities. These agencies may already have characterized ground water resources in the State, and may also have collected data about current and potential land use, aquifer sensitivity and vulnerability, and current and potential aquifer use.

A thorough review of existing resource assessment data, including reports and maps produced by other agencies, will allow managers to identify and prioritize areas where more data are needed. In some States, such a review may show that sufficient information exists to perform an initial assessment. It is likely, however, that the quality of existing data will vary across the State, and that a complete resource assessment will require considerable additional research. The State will need to find the funding and expertise to accomplish this research.

Role of EPA and Other Federal Agencies in State Ground Water Resource Assessments

EPA's primary role in State resource assessments is to assist States in conducting technically sound, comprehensive, Statewide assessments that can serve as a basis for setting CSGWPP priorities. EPA provides funds to States, through Section 106 of the Clean Water Act, that can be used for resource assessments. In addition, EPA regional offices can provide technical assistance and encourage the consistency of programs in areas where different States share a common aquifer. Regional offices can also help identify sources of data and information.

The recently published Handbook for State Ground Water Managers (USEPA, 1992b) identifies Federal programs that may provide information and funding to States for conducting ground water resource assessments. EPA also promotes cooperation in providing technical assistance among its own programs and Federal agencies such as the U.S. Geological Survey (USGS), Department of Defense (DOD), National Oceanic and Atmospheric Administration (NOAA), Department of Agriculture (USDA), and Department of Energy (DOE) in helping States to develop resource assessments. In addition, the Federal Interagency Committee on Water Data's Subcommittee on Ground Water has prepared a comprehensive Directory of Federal Ground Water Programs (in progress), which includes sources of information useful in resource assessments.

Resource Assessment Process

By its nature, resource assessment is an iterative process. As new and better data are collected, and as currently available resource descriptions or maps are used to make decisions, managers will identify additional locations or parameters that should be studied. The best professional judgement of ground water scientists and hydrologists plays a critical role in this process, particularly during the data collection and interpretation stages. How a resource assessment is ultimately used may also be a factor in determining the best way to conduct the assessment.

This document identifies ten **Components** of a ground water resource assessment. *These Components address the physical and chemical characteristics of an aquifer.* Together they provide a comprehensive characterization of a State's ground water resources, including a description of the quality and quantity of water underlying a State, the matrix through which the water moves, and the recharge and discharge areas associated with the ground water reservoir.

These ten Components are:

(1) Regional Hydrogeologic Setting -- Hydrogeologic factors that control the regional occurrence, movement, and availability of ground water: hydrogeology, topography, regional climate, hydrography, soil, vegetative cover, regional recharge and discharge patterns, ground water quality, geochemistry, and geophysical characteristics

(2) Aquifer and Aquifer-System Occurrence -- Areal distribution and three-dimensional position of aquifers in the geologic sequence

(3) Water Table and Potentiometric Surface -- Water table: the upper surface of the saturated portion of an unconfined aquifer. Potentiometric surface: water surface elevation to which water will rise in a well tapping a confined aquifer

(4) Hydraulic Properties -- The properties of soil, rock, sediment, and other geologic materials that govern the movement of water into, through, and out of an aquifer

(5) Confinement and Interaction Between Aquifers -- Ease with which leakage between aquifers can occur. The greater the confinement, the less the interaction

(6) Ground Water Recharge and Discharge Characterization -- Where, and at what rate, aquifers are recharged by infiltrating precipitation and ground water is discharged to the land surface

(7) Ground Water and Surface Water Interaction -- Where, and at what rate, water moves between an aquifer and a body of surface water

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(10) Ambient Ground Water Quality -- The quality of ground water at a baseline time selected by the decision-making agency. Ambient quality may be the natural quality of ground water or may be the quality as impacted by widespread historical contamination. (Some aquifers may be naturally unsuitable for a variety of uses, while others are unsuitable as a result of contamination)

In addition to identifying these Components, the resource assessment process includes four different **Approaches** to assessing ground water. *These Approaches combine the physical and chemical components with human activities to better explain the potential impact of those activities on the ground water resource.*

The four Approaches presented in this document are:

(1) Aquifer Sensitivity -- The relative ease with which a contaminant applied on or near the land surface can migrate to an aquifer of interest. An aquifer's sensitivity is a function of the intrinsic characteristics of the geologic materials in question and the overlying saturated and unsaturated materials. Aquifer sensitivity is independent of land use and contaminant characteristics

(2) Aquifer Use -- Quantification of ground water withdrawal rates and identification of types of use. This information allows managers to determine future trends in ground water use, to plan for changes, or to modify existing practices

(3) Land Use -- Uses of land may affect ground water resources. The type of land cover, including vegetation and manmade alterations such as pavement, directly affect the runoff and infiltration of precipitation

(4) Ground Water Vulnerability -- The relative ease with which a contaminant applied on or near the land surface can migrate to an aquifer under a given set of land use management practices, contaminant characteristics, and aquifer sensitivity conditions

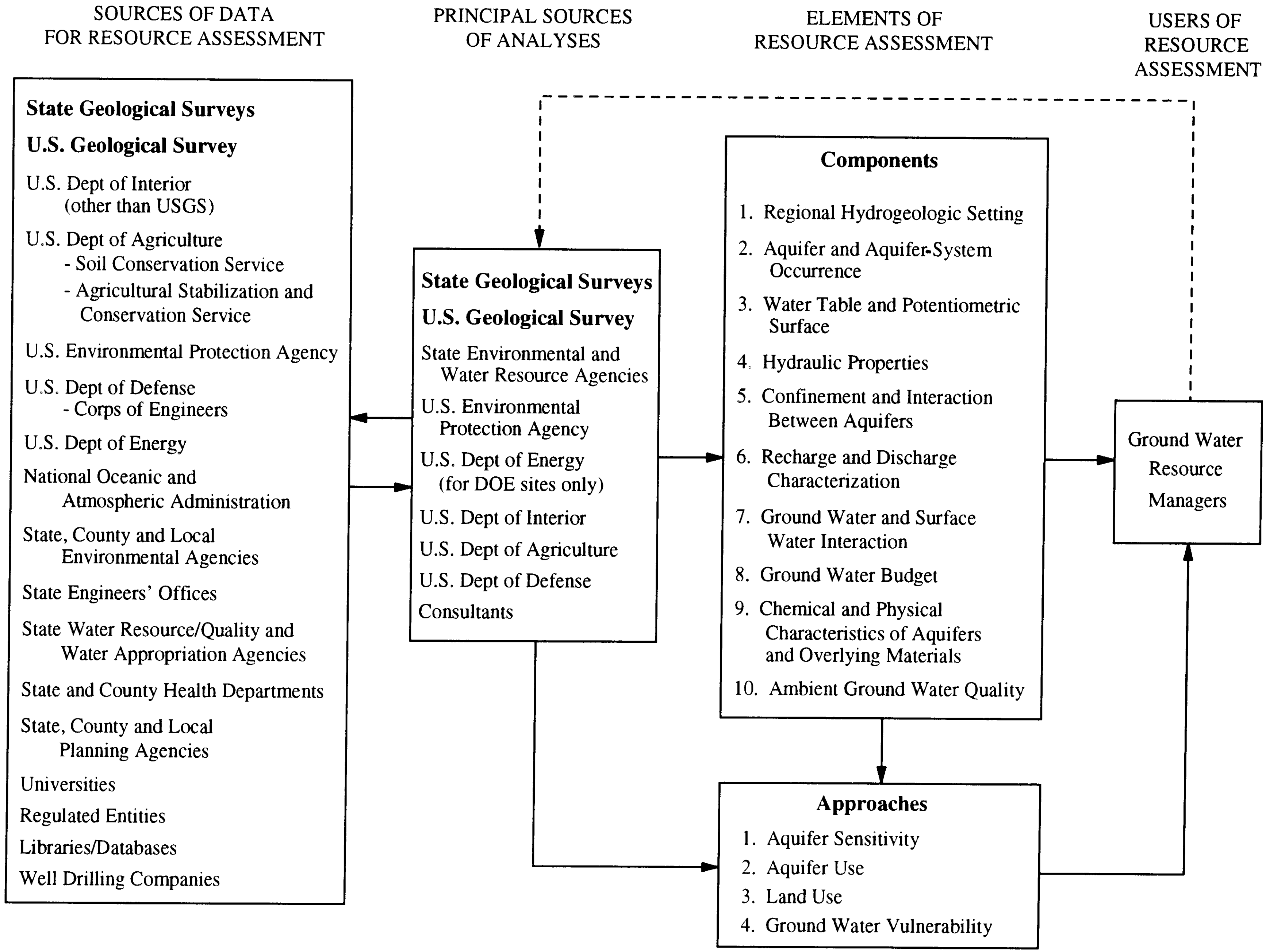
Appendix A presents an initial list of characteristics to be considered when conducting a ground water resource assessment. This list is from the National Guidance for CSGWPP. The technical and hydrogeologic factors in the list have been incorporated, expanded, and reorganized in this document.

States are encouraged to select those Components and Approaches that are most relevant to their own needs. Explanations of the Components and Approaches in this document were written to stand alone, with some overlap in the descriptions, because States will most likely choose to perform some, but not all, of them. The Components and Approaches are meant to apply everywhere, although certain modifications may be necessary in unique areas of the country.

Table 1 shows the flow of information among data sources, resource assessment providers, Components, Approaches, and the end users of resource assessments. The table depicts *all* Components and Approaches as being part of a complete resource assessment, but States may choose only those that they deem necessary. An aquifer sensitivity or ground water vulnerability assessment is not necessary to the resource assessment process, but either type of assessment would aid State ground water protection management efforts by helping to determine the relative susceptibility of different geographic areas of a State to contamination. If a State chooses to perform a sensitivity or vulnerability assessment, it will first have to perform those Components it considers necessary to characterize its ground water system.

Additionally, a vulnerability assessment requires that the State complete the Land Use and possibly the Aquifer Use Approaches. A sensitivity or vulnerability assessment helps managers use data from the resource assessment Components in making decisions about ground water protection.

TABLE 1
FLOW DIAGRAM OF GROUND WATER RESOURCE ASSESSMENT INFORMATION



Use of Resource Assessments for Decision-Making

EPA recognizes that decision-making processes differ among States. For many States, government agencies will conduct or may have already conducted the resource assessment. In other States with ground water protection priorities based on a sound resource assessment methodology, consultants or other non-government personnel may conduct assessments that update or refine information for a given area.

States can begin the resource assessment process by using existing information as well as data acquired from ongoing programs to develop a preliminary resource assessment for setting initial protection priorities. These activities could be followed by data collection and analysis for geographic areas where information is sparse or absent.

Under a CSGWPP, States can base their protection and management priorities partly on the results of a Statewide resource assessment. Federal agencies can in turn use the priorities established by States to manage Federal programs related to ground water.

Resource Assessment in Perspective

Due to the wide areal extent of ground water resources (as compared to surface waters), the protection of ground water requires the setting of priorities, since resources (i.e., people and money) are always limited. The fundamental objective of ground water resource assessment, therefore, is to provide a "resource-based" framework for making decisions and setting priorities. States that assess their ground water resources will be able to better focus the efforts of both Federal and State programs (e.g., Superfund, Underground Storage Tank, Nonpoint Sources) aimed at protecting the resource.

"Resource-based" decisions consider ground water as an overall resource rather than limiting consideration to ground water at or adjacent to a single site. This "resource-based" approach recognizes the integral role of ground water in the hydrological/ecological system.

Organization of This Document

- Chapter 1 gives an introduction to ground water resource assessment

- Chapters 2 and 3 describe the individual Components and Approaches of a resource assessment. These chapters describe data gathering, presentation, and analytical methods used to develop an overall resource assessment

- Appendix A is an initial list of characteristics to be considered when conducting a ground water resource assessment

- Appendix B presents five case studies that illustrate the implementation of resource assessments and how they were used in decision-making

- Appendix C lists sources of hydrogeological information

- Appendix D provides a glossary of selected terms used in this document

Citations

U.S. Environmental Protection Agency, 1992a. Final Comprehensive State Ground Water Protection Guidance (EPA 100-R-93-001). Office of the Administrator, 135 p.

U.S. Environmental Protection Agency, 1992b. A Handbook For State Ground Water Managers (EPA 813-B-92-001). Office of Water, 21 p.

U.S. Environmental Protection Agency, 1991. Protecting The Nation's Ground Water: EPA's Strategy for the 1990's (21Z-1020). Office of the Administrator, 84 p.

CHAPTER 2:

Components of a Ground Water Resource Assessment

A ground water resource assessment begins with an evaluation of the resource based on a number of discrete Components, which are described in detail in this chapter. Resource managers may choose to consider only those Components that are critical to State priorities.

Knowledge of the basic characteristics of ground water and the materials through which it flows is important for understanding larger issues such as the quantity and quality of the overall resource. The Components in this chapter deal with the collection, analysis, and presentation of basic hydrogeologic data. These data give managers the background information needed to assess aquifer sensitivity and ground water vulnerability as described in Chapter 3. They also provide a basis for making decisions that affect the resource, such as water supply development, siting of waste handling and disposal facilities, dealing with existing aquifer contamination, and setting priorities for protection programs.

Establishing goals and objectives is an important first step in a resource assessment that should not be overlooked. Resource managers also should develop a data collection plan that considers data storage and retrieval capabilities, data format and quality, and resources needed to analyze the data. Collection of hydrogeologic information should be coordinated among government agencies to ensure efficiency.

The U.S. Geological Survey (USGS), State geological surveys, and other State water research agencies have missions that include the evaluation of ground water resources. Because of the technical nature of the required data, these agencies can provide managers with resource evaluations, as needed. Reporting all the elements of the Minimum Set of Data Elements for Ground Water Quality (USEPA, 1992) facilitates the sharing of information among agencies and enhances the resource assessment process.

Defining a study area also is important. Because geologic conditions can vary over short distances, collecting data in a small area is often necessary to determine local geologic conditions. Because resource managers are often more concerned with ground water resources on a regional level, it is recommended that managers consider the aquifer or aquifer system as a whole. The manager should be aware, however, that a regional depiction is based on information acquired from site-specific and well-specific data, which include their own assumptions.

The limitations of existing data, and of data collected through new studies, affect how the data can be used. Such limitations include geographic scale and reliability. It is often necessary to collect new data to correlate and verify results of previous data collection efforts. Hydrogeologists and other ground water professionals should be involved in determining the adequacy of data or data collection methods and ensuring that sound scientific judgement and techniques are used in the resource assessment process. The USGS, State geological surveys, and other State water resource agencies have the relevant mission and expertise to provide managers with ground water resource evaluations, as needed.

The resource assessment Components listed in this chapter, taken together, constitute a rational, step-wise process for collecting hydrogeologic data and information. Information produced for each Component will facilitate completion of the next Component.

The ten Components are:

(1) Regional Hydrogeologic Setting
(2) Aquifer and Aquifer-System Occurrence
(3) Water Table and Potentiometric Surface
(4) Hydraulic Properties
(5) Confinement and Interaction Between Aquifers
(6) Ground Water Recharge and Discharge Characterization
(7) Ground Water and Surface Water Interaction
(8) Ground Water Budget
(9) Chemical and Physical Characteristics of Aquifers and Overlying and Underlying Materials
(10) Ambient Ground Water Quality

The discussion of each Component is broken into the following subsections:

- Definition

- Objective
- Data Needs
- Methods
- Presentation of Data/Information
- Considerations
- Citations

Citations

U.S. Environmental Protection Agency, 1992. Definitions for the Minimum Set of Data Elements for Ground Water Quality (EPA 813/B-92-002). Office of Water, 98 p.

Component #1: Regional Hydrogeologic Setting

Definition

For the purposes of this discussion, regional hydrogeologic setting is an area of broad extent (a county, State or multi-State area) with common geologic and hydrologic features that control ground water movement in, through, and out of the area (Aller, et al, 1987). These features include stratigraphy, the nature of water-bearing openings of the aquifers and confining beds, major recharge and discharge characteristics, hydrogeologic divides, and other physical, chemical, and hydrologic features.

Objective

The objective of this Component is to establish the regional hydrogeologic setting that provides a general framework for the characterization of aquifers. This information helps frame exploratory, evaluative, or management studies of ground water. This information also improves the predictability of encountering any given geologic unit at specific sites and improves confidence in the conclusions of ground water management studies. Obtaining and evaluating regional hydrogeologic information is generally cost-effective because regional information is typically collected, compiled, and distributed by government agencies.

Data Needs

Selected data such as those listed below are needed to describe the regional hydrogeologic setting:

- hydrogeology
- topography
- regional climate
- hydrography
- soil and vegetative cover

- regional recharge and discharge patterns
- ground water quality/geochemistry

When evaluated at a regional scale, these data contribute to the overall understanding of the hydrogeologic setting. If managers desire a more localized study (i.e., one conducted at a larger scale), it is more appropriate to collect data at more closely spaced points. Because of the various constraints encountered in the collection of data, it is important to determine data needs and carefully plan data collection activities at the beginning of a resource assessment.

Hydrogeologic data form the basis for understanding hydrogeologic settings. These data describe the major geologic and hydrologic factors that control ground water storage and movement into, through, and out of an area. From these data, it is possible to make generalizations about both ground water availability and pollution potential. Hydrogeologic data include hydraulic conductivity, storativity, and transmissivity of the vadose zone and aquifer; the mineral composition of the water-bearing matrix; and the geology of the hydrologic unit(s) (i.e., both aquifers and confining beds).

Hydrologic parameters such as hydraulic conductivity, storativity and transmissivity help define an aquifer's ability to store and transmit ground water and effect the rate of movement of pollutants. For more information on the hydraulic properties of geologic materials, see Component #4.

The nature of the water-bearing matrix relates to the kinds of openings, primary pores and fractures in which ground water can be stored and transported; the solubility of the matrix is in part determined by its mineral composition. These matrix characteristics influence water storage and transmission, the dispersion and dilution of pollutants, and ambient water quality. For more information concerning the physical and chemical characteristics of aquifer materials, see Component #9.

Information about geology and landforms provides the framework for studying ground water flow volume, direction, and quality. Information about geologic structures (e.g., faults, folds, and intrusions) is critical in defining the location and extent of aquifers, especially in the western United States. For example, faulting may truncate water bearing units or connect them to other permeable units. Stratigraphic data describe the geometrical and age relations (i.e., relative order of occurrence with depth) among geologic lenses, beds, and formations. Stratigraphic data help identify the occurrence of water-bearing units and the spatial relations that exist between the water-bearing and non-water-bearing units.

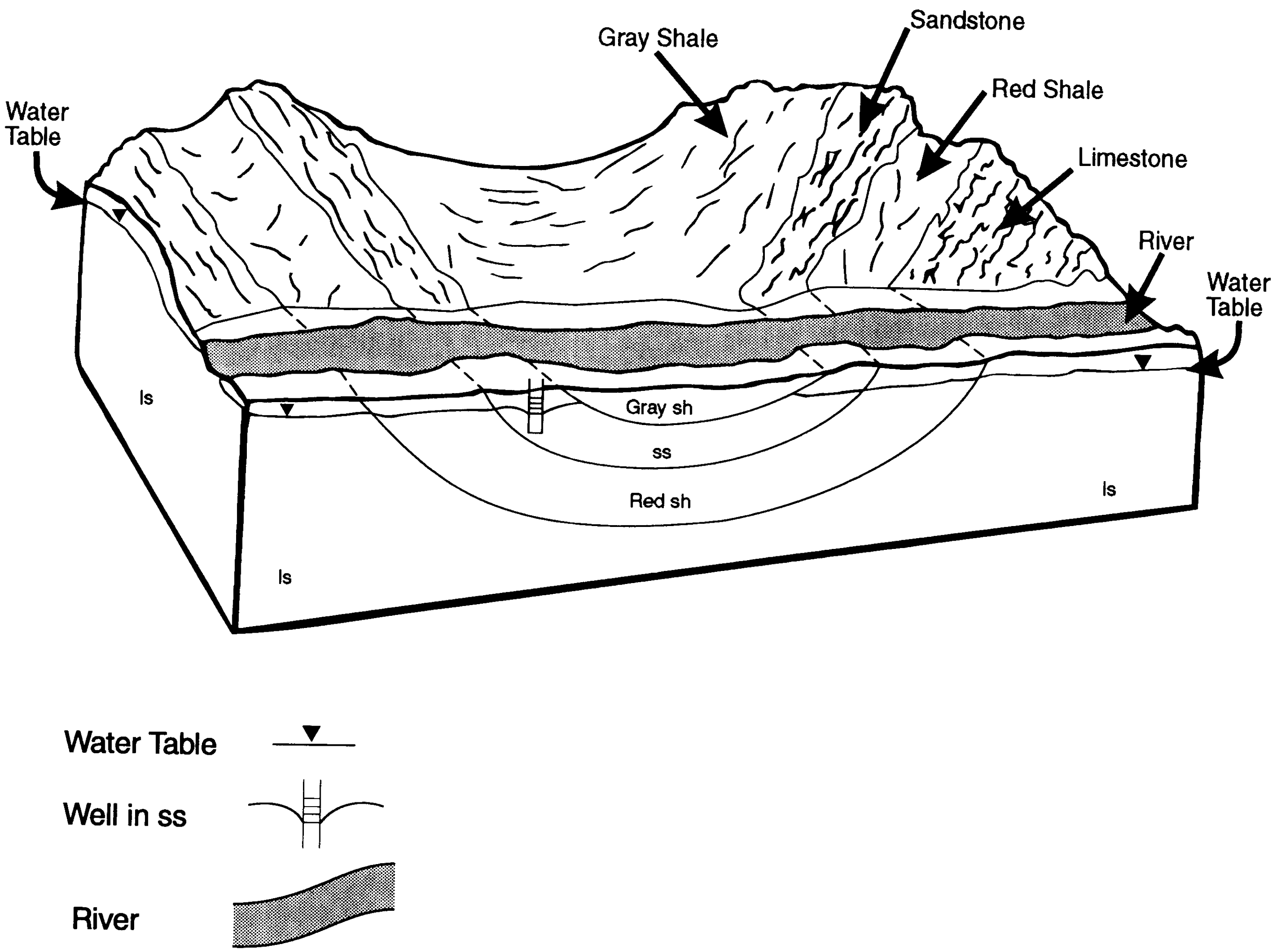
Topographic data help to determine the extent and direction of surface water flow and are necessary to determine the elevation of the water table. In many hydrogeologic settings, highlands are ground water recharge areas (i.e., areas where water enters the ground water reservoir) and lowlands are ground water discharge areas (i.e., areas where water exits the ground water reservoir). Diverse topographic features, even in basins underlain by consistent and homogeneous geologic materials, can create a complex system of ground water flow. Where local topographic relief is negligible, ground water flow systems may be more regional. Where local relief is pronounced, ground water flow systems may be more local (Freeze and Cherry, 1979). Topographic data can play a vital role in selecting the appropriate scale for collecting, evaluating, and displaying hydrogeologic data. Figure 1 shows a regional hydrogeologic setting (USGS, 1992).

Data describing the **regional climate** are critical to assessing the regional hydrogeologic system. Climatic data are necessary to evaluate the recharge, storage, and occurrence of ground water. These data include the quantity and pattern of precipitation, average and extreme temperatures, and evaporation rates. Both areal and temporal patterns of climatic events are important.

Hydrographic data provide valuable information on the location, extent and flow of surface water bodies (e.g., lakes, rivers, wetlands). This information is relevant to determining ground water recharge and discharge areas and is necessary for defining areas of ground water and surface water interaction. The information is critical for a complete evaluation of a ground water budget (i.e., an accounting of water movement into and out of the ground water system). For more information on the use of surface water data for determining ground water characteristics, see Component #7.

Data on the **soil and vegetative cover** help identify recharge areas and infiltration and transpiration rates. Soil characteristics are a major influence on infiltration rates. Types and amount of vegetative cover determine the amount of precipitation intercepted and used

Figure 1
Block Diagram Showing a Regional Hydrogeologic Setting



Source: After USGS, 1992

(transpired) and therefore, unavailable for recharge. Coefficients for soil and for vegetation based on type and percent cover are necessary inputs to the equations and computer models that calculate water balances of geographic regions. In addition to soil and vegetation data in areas of karst topography, information on surficial features such as the location and general characteristics of sinkholes, surface fractures (lineaments), solution features (e.g., sinking streams, caves), and all possible points of direct recharge to karst aquifers, should be obtained.

Regional recharge and discharge patterns identify where water enters (recharges) and exits (discharges) ground water systems. Data defining recharge and discharge locations help identify areas that contaminants can enter and exit the ground water system. Recharge areas are typically areas where contaminants can more easily enter ground water. Contaminants in the ground water are likely to exit in ground water discharge areas. For further discussion of the characterization of ground water recharge and discharge areas, see Component #6.

Ground water quality/geochemistry data describe the presence and concentration of natural and human-induced biological, radiological, and chemical constituents in water and provide information to help determine the appropriateness of the water for its intended purpose: agriculture, industry, and domestic and municipal consumption. For example, ground water quality/geochemistry data can be used for such purposes as determining the safety of drinking water supplies. Baseline data can be used to establish ground water quality trends. Constituents dissolved in ground water provide clues to its geologic history and may yield information on the rocks and soils through which the water has flowed. For information on ambient ground water quality, see Component #10.

Methods

Several methods can be used to obtain the data described above. The most cost-effective initial method is a literature search. A search for existing data and information frequently reduces the need for additional field work. The search could include both published and unpublished materials, such as: maps, circulars, reports, monographs, and aerial photographs. Existing data sources should be analyzed for level of detail, potential applicability and representativeness. Soil, geologic, hydrographic, and topographic data are often available from maps and reports published by government agencies (e.g., the U.S. Geological Survey (USGS), State geological surveys, the U.S. Department of Agriculture's Soil Conservation Service (SCS), the USGS Earth Resources Observation System (EROS) Data Center, and the National Weather Service), and universities. Additionally, universities may provide theses and dissertations containing relevant information and additional references. County and local planning agencies often collect aerial photographs that may provide supplementary information on the landforms, soils, and vegetation of their region. Climatic information (e.g., precipitation, temperature, and weather patterns) can be obtained from the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service, and universities having climatology or meteorology programs.

Several methods have been developed to organize and interpret hydrogeologic data (see, for example, Heath, 1984; Johnston and Bush, 1988). In general, these methods use hydrogeologic data to delineate and describe ground water regions across the United States. Heath, for example, uses hydrogeologic data to divide the continental United States, Puerto Rico, and the Virgin Islands into 15 distinct ground water regions. By referring to these and similar regional studies, ground water resource managers can learn a great deal about the hydrogeology of their region. Managers should understand, however, that these studies are regional in scope, and will not reflect local variations in hydrogeology.

Site-specific data can be used to complement regional data where necessary. Existing data bases or clearinghouses, such as those available through the USGS, State geological surveys, and State Engineers' Offices, often provide site-specific data (e.g., test hole and well data). Well logs are another useful source of site-specific data and are often readily available. A comprehensive review of all available well logs may be highly resource intensive; however, if well logs are computerized, careful screening and selection of logs for detailed review reduces needed effort.

After a review of sources of existing data, a list of additional information needs can be prepared to identify where field mapping activities are needed. This list should include the exact nature of the data required, the applications and analyses that the data will be expected to support, and the most efficient means of obtaining and managing the data. Depending on the extent of previous geological field mapping activities, future mapping can be planned according to State priorities. Geologic mapping is primarily the responsibility of State geological surveys and the USGS. Additional mapping may be conducted by State and local universities. Soil mapping is performed by the SCS. Once data are compiled, an interpretation of the regional hydrogeologic setting is possible.

Presentation of Data/Information

Geologic maps are a fundamental vehicle for the display of geologic information. Geology, topography, soils, hydrography, water table and potentiometric surfaces, water quality, climatic variables such as precipitation, and other information are commonly displayed on maps or cross-sections. Maps can also illustrate relationships such as between soils and the stratigraphy of underlying geologic materials (including aquifers). Such representations have numerous applications, including assessing the potential for aquifer contamination (Soller and Berg, 1992). Because many combinations of soils and hydrogeology are possible, overlays of different data sets that aid in focusing analyses may be particularly useful. Computer applications, including the use of Geographic Information Systems (GIS), may significantly ease the overlay process and, if the maps are in a digital format, may be cost-effective. The use of GIS requires the careful checking of all output, particularly for discrepancies in depiction of topography, evidence of input errors, and errors in site locations of input data. Although GIS output from existing data sets is relatively inexpensive to obtain, the time and expense to create new data sets and to maintain a GIS must be carefully considered. Some personal-computer-mapping software also can be used to help in the preparation of simple maps.

Geologic data may also be displayed three-dimensionally. For example, fence diagrams illustrate a series of intersecting geologic cross-sections. Stack-unit maps show the three-dimensional distribution of geologic materials in their order of occurrence of depth, over a specified area and depth (Kempton, 1981). Block diagrams (see Figure 1) also present a three-dimensional view of the hydrogeologic setting.

Considerations

Small-scale regional geologic maps are frequently available. For example, many States publish a "State geologic map," often at a scale of 1:500,000. Data from these maps are highly generalized and not intended for site-specific use. Small-scale studies are typically based on regional settings ranging from counties to multi-State areas. Intermediate scales ranging from 1:100,000 to 1:250,000 are also used for regional assessments. Data and information on geology, soils, and topography are commonly compiled at these scales.

Regional maps are a very useful tool for identifying areas for more site-specific investigations. A convenient scale for many site-specific investigations is 1:24,000, the scale at which topographic information is available from the USGS for much of the United States. In many States, less than ten percent of the area is adequately mapped at this scale. 1:24,000 is also the scale that will be used by many States to compile geologic information under the recently passed Geologic Mapping Act of 1992 (P.L. 102-285). The purpose of this Act is to expedite the production of a geologic-map data base for the Nation to assist in the resolution of issues related to land-use management, assessment, utilization and conservation of natural resources, ground water management, and environmental protection. The Act designates the USGS as the lead Federal agency responsible for overall management of this national program.

As more site-specific data are collected over a large study area, the regional interpretation based on site-specific data becomes increasingly accurate. This increasing accuracy, in turn, results in better predictability when conducting site-specific studies. There is, therefore, a continual feed-back process whereby site-specific information improves the regional data base, and the improved regional data base increases the understanding of hydrogeology at specific locations. The resources required to collect existing hydrogeologic data are generally limited by the availability of staff. When collection of site-specific data is required, field surveys, drilling or other field operations, and/or the obtaining of aerial photographs will be needed. These activities are generally expensive and time-intensive. Typically, geologists must visit the site in question and appraise the surficial and subsurface hydrogeologic characteristics. Drilling rigs may be required to drill test holes and to install ground water monitoring wells to obtain the additional data desired.

The use of a GIS to assist in data interpretation requires a sophisticated computer system and additional staff time to manage the data. GIS may be used to assist ground water scientists by producing initial estimates of the positions of hydrogeologic boundaries and features, and the positions of parameter contours; the limitations of such interpretations must be recognized.

In most States, much of the information referred to above is available. The information used to describe the regional hydrogeologic setting provides the larger framework for making decisions on additional data needed for a resource assessment to support State ground water policy.

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Component #2: Aquifer and Aquifer-System Occurrence

Definition

An aquifer is a geologic formation, group of formations, or part of a formation that contains sufficient saturated, permeable material to yield significant quantities of water to wells or springs. An aquifer system is a combination of permeable and less permeable materials that function regionally as a water-yielding unit (USGS, 1989). Aquifer and aquifer-system occurrence refers to the areal distribution and position of an aquifer or aquifer system, including its depth below the ground surface, thickness, areal extent, and hydrologic boundaries (i.e., the natural geologic and hydrologic characteristics that define the aquifer).

Objective

The objective of this Component is to focus the resource assessment on geologic units that are logical ground water management units. Knowledge of the geometry and geology of an aquifer or aquifer system facilitates protective resource planning (e.g., appropriate siting of facilities that are potential sources of contamination) and prioritizing the remediation of contaminated sites.

Data Needs

Geologic and hydrologic data are needed to define the occurrence of aquifers and aquifer systems in three dimensions. These data include:

- saturated thickness of the aquifer system
- depth to top and bottom of individual aquifers
- areal extent
- geophysical characteristics

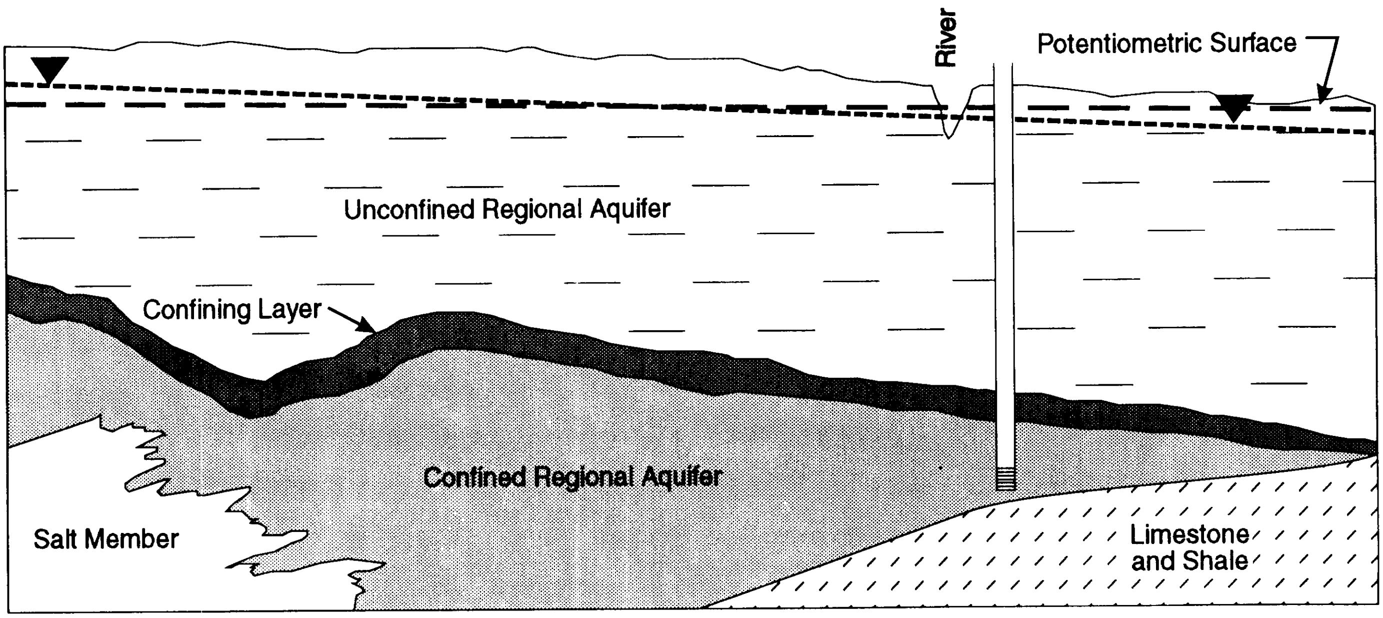
Knowledge of the lithology (i.e., composition and texture) of geologic units provides general information about the potential of those units to function as an aquifer. The stratigraphic arrangement of geologic units is needed to define the relationship between aquifers and aquitards. Knowledge of the regional geologic sequence will assist investigators in identifying the types of aquifers throughout the region or study area. Figures 2 and 3 (after Moody, et al, 1988) illustrate the influence of geologic structure on the occurrence of regional aquifers. For example, in areas where geologic materials have low primary porosity and primary permeability (e.g., igneous or metamorphic rocks), aquifer hydraulic conductivity is controlled by the presence of fractures, faults, or other conduits.

Saturated thickness of the aquifer system is defined as the entire zone of saturation of unconfined and/or confined aquifers. The upper surface of the zone of saturation of an unconfined aquifer is called the water table. In general, the water table is a subdued reflection of the surface topography and lies at greater depth under hills than under valleys; however, the depth to the water table in an unconfined aquifer is subject to seasonal variation causing a change in the thickness of the saturated zone (USEPA, 1987). The saturated thickness of an unconfined aquifer is the distance between the water table and the top of the first underlying confining unit. The potentiometric surface of a confined aquifer, which is the surface defined by the level to which water would rise in wells penetrating a confined aquifer, can also vary seasonally, but this variation does not cause a change in saturated thickness unless the water level drops below the aquifer's upper confining bed.

Saturated thickness is used with other parameters to determine the transmissivity of an aquifer system and to estimate the volume of ground water in storage. Transmissivity is the total amount of water that can be transmitted horizontally through the aquifer system's full saturated thickness (Freeze and Cherry, 1979).

The **depth to the top and bottom of individual aquifers** defines aquifer thickness. In unconfined aquifer settings, the depth to the top of the aquifer is often important in defining surface water occurrence and connection with ground water. Locations of confining layers and aquifers help define interrelationships within an aquifer system and the extent of regional continuity of aquifers.

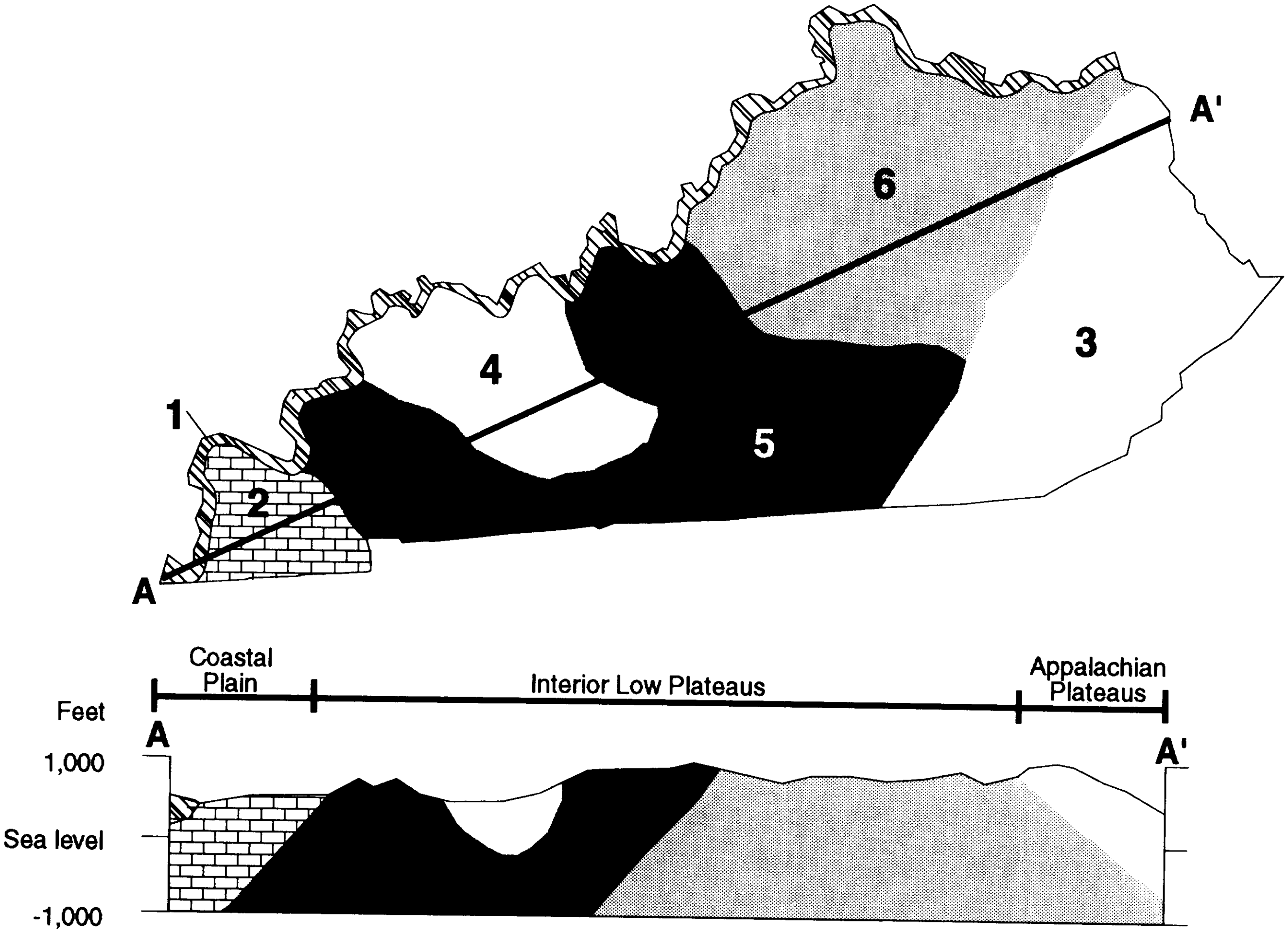
Figure 2
Cross Section Depicting Regional Aquifer



Horizontal Distance is Approximately 10 Miles

Source: After Moody et al, 1988

Figure 3
Map and Cross Section Showing the Regional Aquifer Systems of Kentucky



A -A' Trace of hydrogeologic section

PRINCIPAL AQUIFERS

(1) Alluvial

(2) Tertiary and Cretaceous aquifers

(3,4) Pennsylvanian aquifer system

Eastern Kentucky Pennsylvanian aquifers (3)

Western Kentucky Pennsylvanian aquifers (4)

(5) Mississippi aquifer system

(6) Ordovician aquifer system

Source: After Moody et al, 1988

The **areal extent** of an aquifer or aquifer system is directly related to its geology. Aquifer/aquifer system are composed of those portions of a geologic formation(s) that can provide significant water to wells. The extent of geologic formations is finite due to the intrinsic characteristics of their environment of deposition and their modification by natural geologic processes. For example, formations may thin out or "pinch out", crop out at the surface, or may be truncated by faulting, plutonic intrusions, or erosion. Areas of significant water yield may be considerably smaller than the full extent of the geologic formation(s) due to lithologic variability within the formation(s).

Geophysical data may enhance understanding of the three-dimensional geometry of, and relationships among, aquifers and aquitards. Geophysical techniques are sometimes employed to locate ground water resources and to assess spatial characteristics of aquifer/ aquifer systems. Techniques frequently used to gather geophysical data include seismic refraction, electrical resistivity, electrical conductivity, and ground penetrating radar (GPR). Analysis and interpretation of these data can provide an estimate of the extent of water-bearing materials. Hydrogeologists can then verify their interpretations with well information and plot the extent of the aquifers.

Methods

Similar to all other Components, data for characterizing the occurrence of aquifers and aquifer systems can be obtained from existing sources and from collecting new field information. In some cases, existing information will be sufficient to delineate the geometry and lithology of aquifers and aquitards. Aerial and satellite imagery, if available, may provide cost effective information on the areal extent of aquifers. If sufficient data are lacking, geologic mapping and lithologic analyses or other techniques will be required to define the occurrence of aquifers.

The U.S. Geological Survey (USGS), State geological surveys, State water quality and water research agencies, and universities commonly collect the types of hydrogeological data needed to assess the occurrence of aquifers and aquifer systems. Once collected, these data are relatively inexpensive for other agencies to obtain and are usually highly reliable. The data may be interpreted in the form of maps, cross-sections, fence diagrams, or stratigraphic columns showing the relative age and location of geologic formations in the study area. Also, numerous published and unpublished reports exist for local and regional aquifers located throughout the United States.

Most major aquifers and aquifer systems in the United States have been identified and mapped. However, many glacial drift aquifers in the Midwest are poorly documented. The USGS's Regional Aquifer System Analysis (RASA) program is systematically studying the major aquifers and aquifer systems in the United States. The program consists of studies of 28 aquifer systems across the U.S.; more than three-fourths of the program studies are completed. The studies present an assessment of regional geology, discharge and recharge dynamics, hydrogeology, and geochemistry. The USGS is also publishing a "Ground Water Atlas of the United States," which is a series of regional atlases presenting text, maps and other figures that synthesize information from the RASA program and related studies. The Atlas is scheduled for completion in 1994.

If significant data gaps are identified, additional test drilling and geologic field mapping may be necessary. Test drilling and well drilling provide an opportunity to: compile logs of geologic materials, core or otherwise sample the materials, identify the presence of aquitards, characterize overlying soil and unsaturated (i.e., vadose) zone materials, and measure depth to water.

Detailed geologic mapping provides information on the lithology, structure, and stratigraphy of the geologic formations. The process of geologic mapping requires developing detailed notes on geologic formations, formation bedding trends, structures, and other geologic information. Field notes and field maps provide the information for the development of surface and subsurface geologic maps and cross-sections. These products, combined with information about hydraulic properties can be used to define aquifer and aquifer system occurrence.

Geophysical techniques may provide site-specific or regional data. The nature of the information obtained depends on the technique applied. For example, gamma and electrical resistivity logging allow interpretations of the physical properties of the subsurface geologic materials for a specific borehole. Surface-based geophysical techniques can sometimes be used to interpolate between areas of ground truth (e.g., boreholes, wells). These techniques may be relatively rapid to perform, and can be very cost effective (Zohdy, et al, 1974; Keys, 1990).

Presentation of Data/Information

The areal extent and thickness information collected for a specific aquifer or aquifer system may be compiled into maps, fence diagrams or geologic cross-sections. Contour maps can also be developed to present such information as the elevation of the water table and top or base of an aquifer. The saturated thickness of unconfined aquifers may vary with season and well pumpage, and therefore, more than one saturated-thickness map or water-table map may be desired. Where hydraulic properties are fairly uniform, aquifer thickness can be used to evaluate the areas of greatest potential for well-field development; elsewhere, transmissivity maps should be used for well-field siting.

For ground water protection purposes, it may be appropriate to develop thickness maps of confining materials. The thicker the confining materials, the less likely the aquifer is to become contaminated. Table 2 presents the formats used to depict selected information on aquifer and aquifer-system occurrence. A Geographical Information System (GIS) may be used to assist ground water scientists by producing initial estimates of aquifer or aquifer-system boundaries in three dimensions. Some computer software can also assist in the preparation of simple maps. Maps showing depth to aquifer or confining layer thickness over a geographical area are particularly useful products for ground water protection purposes.

Considerations

The scale of aquifer or aquifer-system delineation depends on the size of the aquifer or aquifer system being mapped. Well logs and test holes provide site-specific information that may be extrapolated over large areas. Although published reports and maps are generally based on numerous data points, more data (ground truth) may be available for some parts of the study area than for others.

Data in published reports and maps are available from many agencies. Collection and accurate interpretation of well-drilling logs reported by private well drillers requires

Table 2
Format for Presenting Selected
Aquifer and Aquifer-System Information

Information Presented	Presentation Format
Areal Extent	Map Fence Diagram Block Diagram
Thickness	Geologic Cross-Section Fence Diagram Block Diagram Isopach Map Stack-Unit Map
Depth to the Top of Aquifer or Confining Layer	Geologic Cross-Section Fence Diagram Block Diagram Stack-Unit Map

professional staff with an in-depth knowledge of the local geologic setting. Drillers' logs from the installation of wells, however, may lack sufficient detail or accuracy to provide worthwhile information. In addition, the location of the drill site as indicated on a private driller's log is often inaccurate and must be verified.

In spite of these drawbacks, drilling logs are an important source of geologic information, particularly if several logs are available for the same general location. Drill cuttings and core samples taken during drilling may help confirm some of the driller's entries or provide necessary detail. It is particularly helpful if information is available from nearby exploratory holes or test holes logged by a geologist to confirm the well driller's log.

The drilling of test holes requires expensive equipment and technical staff to log the test hole and collect samples of the geologic materials. Downhole geophysical techniques can be used to accurately delineate formation changes. Experienced technicians and specialized equipment are required to produce the logs, and geologists/geophysicists are needed to interpret test-hole and geophysical data.

Geologic field mapping requires the judgement of a geologist. It is recommended that a geologist familiar with the State or region of interest conduct the mapping and interpret the results. Relationships shown by geologic maps, cross-sections, and columns are interpolated from field data and should be used carefully with consideration of the uncertainties inherent in gathering and interpreting the information presented.

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Component #3: Water Table and Potentiometric Surface

Definition

A **water table** is the upper surface of the saturated zone of an unconfined (i.e., water table) aquifer. At this surface, hydrostatic pressure approximately equals atmospheric pressure. Under unconfined conditions, the static water level in a well represents the water table. A water table can occur in almost any type of material.

An aquifer is confined if it is overlain by low-permeability materials. Ground water in a confined aquifer exists between low-permeability layers and is generally under hydrostatic pressure greater than atmospheric. A **potentiometric surface** is defined as an imaginary surface representing the elevation to which water will rise in wells penetrating the confined aquifer. Well discharge from a confined aquifer can cause the potentiometric surface to fall below the confining layer, particularly near the well. Figure 4 (USEPA, 1991) is an illustration of a water table and a potentiometric surface.

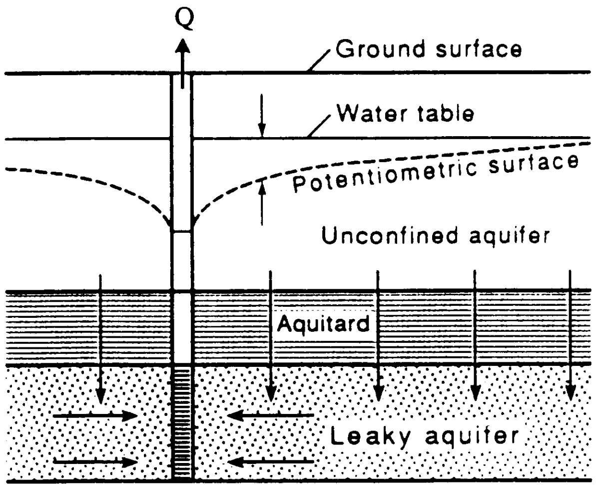
Objective

The objectives of mapping the water table or potentiometric surface are to understand (1) the general direction of lateral ground water flow, (2) the location of recharge and discharge areas, (3) the hydraulic gradient and (4) the hydraulic effects due to pumping, and to obtain information to determine the flow direction and degree of interconnection between an aquifer and adjacent hydrogeologic units and the flow direction and degree of interconnection between ground water and surface water.

Data Needs

To achieve the objectives of this component, the following types of data should be collected:

Figure 4
Schematic Showing Water Table and Potentiometric Surface



Source: USEPA, 1991

- ground water level
- ground water well location

Water-level data from standing wells can be used for a variety of purposes, including: (1) construction of water-table/potentiometric-surface maps, (2) location of recharge and discharge areas, and (3) determination of ground water flow direction and velocity. Water-level data are also needed to determine hydraulic gradient. Data from a well where the water level has been disturbed by pumping must be used with care. Water-level data should be compared only among wells in the same aquifer, because water levels measured in different aquifers at the same geographic location will vary. Therefore, information such as the depth of well screens and other well construction details should be collected.

Well-location data are needed so that the positions of wells can be plotted on a topographic map. Without topographic elevations of wells it is not possible to accurately plot water-level data on a map or draw reliable water-table/potentiometric-surface contours. The accuracy of well-location data is more critical for smaller study areas than for larger areas. Well logs and well registration information collected by Federal, State, and local regulatory programs usually include information on well location and water level. Locations of private wells are often available from well drilling companies, although this source often provides less accurate information. Plotting well locations on topographic maps during field investigations is highly recommended.

Methods

Data collection, management, and analyses for this Component are generally straightforward. Potential data sources include the U.S. Geological Survey (USGS), State geological surveys, State natural resource regulatory and research agencies, local universities, and well drillers' logs. These data sources should be searched to obtain water-level data from existing wells (e.g., monitoring, municipal, or private) installed in the aquifer(s) of interest. If existing wells do not provide adequate water-level data, additional observation wells or piezometers can be installed. Water-level data can be collected using appropriate techniques (e.g., steel tape and chalk, electric probes, downhole pressure sensors, transducers, automated data-collection equipment). Water-level elevations are expressed as feet above some reference point -- generally mean sea level. Wellhead elevations can be obtained by surveying or by approximating from 1:24,000-scale topographic maps.

Once water-level data are obtained for an aquifer of interest, a water-level contour map depicting lines of equal hydraulic head (water level) can be drawn. Data selected for the construction of a water-level contour map should be obtained only from wells screened in the aquifer of interest. If two aquifers are present, a separate map should be drawn for each. The direction of ground water in an aquifer can then be approximated by drawing ground water flow lines perpendicular to contour lines of equal hydraulic head; flow is in the direction of decreasing hydraulic head.

The magnitude of the hydraulic gradient (or change in hydraulic head) can be determined by measuring the change in water-level elevation over a given distance. For example, if the water-level elevation decreases 10 feet in one mile, then the hydraulic gradient is 10 feet per mile. The water level of a given geographic location often varies with depth within an aquifer. In such aquifers, determination of vertical gradients within the aquifer is facilitated by installing clusters of observation wells or piezometers, with each well in the cluster screened at a different depth. A comparison of water levels measured in these wells, in conjunction with well-screen depth, permits calculation of the magnitude of potential vertical water movement in the aquifer. Clusters of wells at the same geographic location but screened in different aquifers can be used to help determine potential interaction between aquifers and potential leakage through confining beds (see Component #5).

Presentation of Data/Information

The common output resulting from an investigation of water levels is a map of the water table/potentiometric surface in an aquifer. Using well-location data, the wells can be plotted on a map with their associated water levels. A contour map of the water table or potentiometric surface is developed by drawing lines of equal water-level elevation. Computer contouring software may provide an initial estimate of contour positions, however, because interpretation between data points is generally required, final maps should be developed by ground water scientists. Directional-flow maps may then be developed from the water-table/potentiometric-surface maps. The scale of data presentation can vary widely depending on the size of the area of interest.

Considerations

Delineating accurate water tables or potentiometric surfaces requires a substantial amount of data. This effort may require the installation of piezometers or observation wells to collect additional data if available data are insufficient. Using steel tape and chalk to collect water-level data from existing wells or piezometers is an economical data collection technique; data loggers with transducers have higher equipment costs but low associated personnel costs. Labor, time, and equipment used to collect and record information will vary according to the size of the particular region or study area, available data and/or data collection points, and the needs of the resource manager.

Four issues should be considered before conducting water-table or potentiometric-surface and ground water flow direction studies.

(1) Collection of water-level data during a single data collection event cannot characterize temporal changes in water-table/potentiometric-surface elevations. Water levels vary with changing seasons and climatic conditions. Therefore, for some purposes, data may have to be collected and analyzed at various times during the year (e.g., wet season and dry season). Regional and local ground water flow directions may vary due to tidal and barometric influences, pumping, irrigation, and impacts from adjacent aquifers and surface water bodies.

(2) Because of seasonal and long-term climatic influences on water levels, water-level contours should be drawn from data collected within a short time period. Comparisons of water-level contours constructed for different measuring periods can then be made to determine possible climatic influence on water levels.

(3) Well installation costs increase not only with an increase in the number of wells drilled but also with well depth. The cost of installing a well will also vary with the local geology and primary purpose of the well, which dictate such factors as well diameter, casing and screen material. The cost of data collection and well installation rises dramatically as the size of the study area, geologic

complexity, or stringency of State and/or local well construction requirements increase. Using existing wells screened at, and only at the depth of interest, can significantly reduce the cost of collecting water-level data.

(4) The concept of a water table/potentiometric surface is strictly valid only for water levels obtained from wells screened in the same horizon in an aquifer that has horizontal flow (Freeze and Cherry, 1979). Most water-table and potentiometric-surface maps, however, are constructed (1) using water-level data obtained from wells installed at different depths throughout an aquifer, and (2) for aquifers that do not have horizontal flow. These factors lead to additional uncertainty in the maps.

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Component #4: Hydraulic Properties

Definition

Hydraulic properties refers to attributes of rock, sediment, and other materials that govern the capacity of materials to hold, transmit, and deliver water. These attributes include effective porosity, maximum and minimum hydraulic conductivity, transmissivity, specific yield, and storativity.

Objective

The objective of this Component is to define the hydraulic characteristics of geologic material. Information about hydraulic characteristics can be used to describe and quantify the occurrence and movement of ground water in aquifers and confining units. Hydraulic data are also necessary to determine well-yield characteristics and determine the movement of contaminants.

Data Needs

The information needed to assess ground water occurrence and flow includes:

- hydraulic gradient
- porosity/effective porosity/fracture porosity
- grain-size distribution
- structural-geology factors
- hydraulic conductivity
- transmissivity
- storativity and specific yield
- ground water velocity

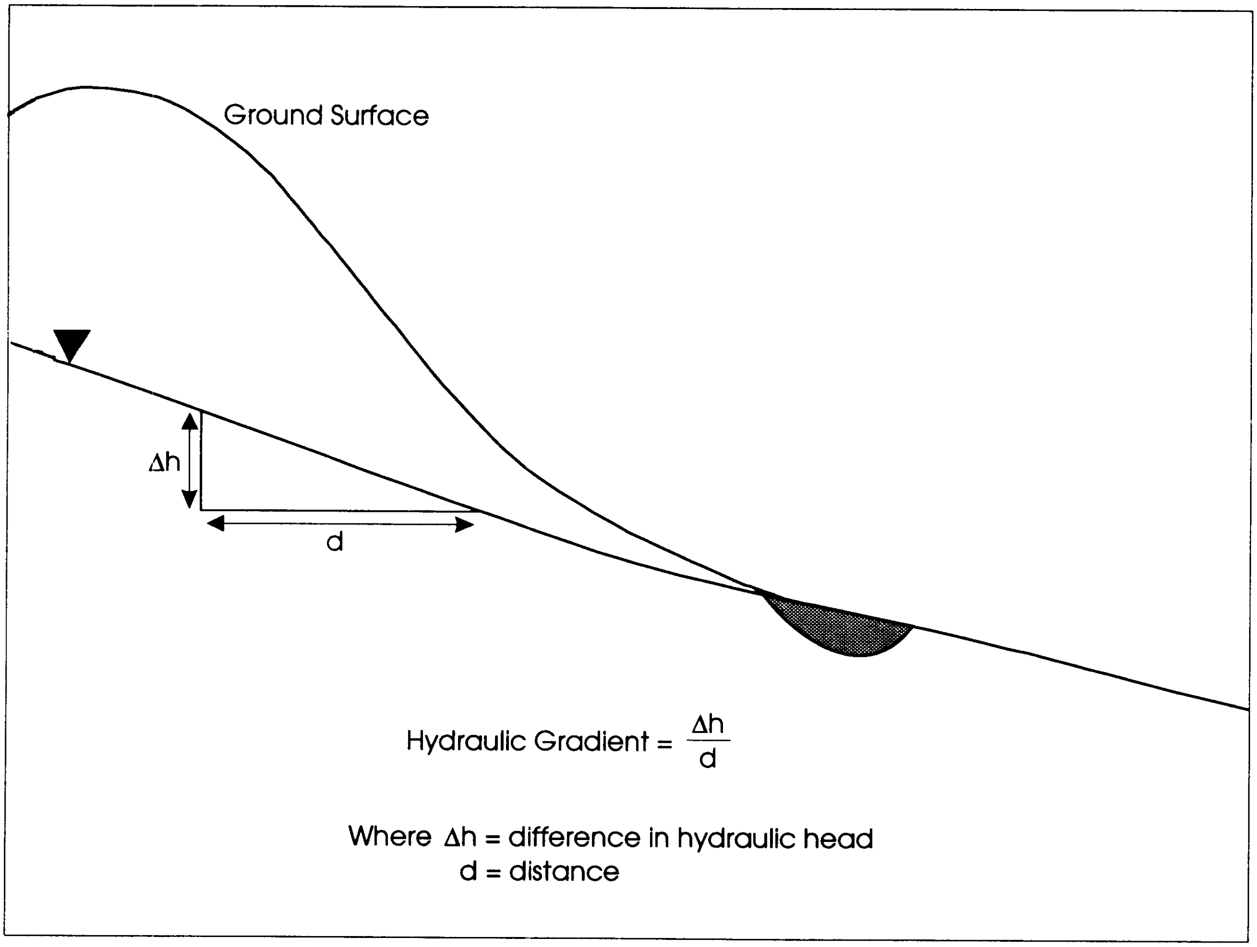
These data are used to estimate amounts of ground water stored in aquifers and other geologic units, quantities of water flowing between surface water and ground water, the amount of ground water flowing between aquifers, and general rates of ground water flow.

Hydraulic gradient is a measure of the change in hydraulic head over a given distance (i.e., the slope of the water table or potentiometric surface). For a graphical illustration of the calculation of hydraulic gradient, see Figure 5A. The direction of the hydraulic gradient is the direction of maximum decrease. Hydraulic head is a general term used to describe the elevation of water above a known datum. Hydraulic head is composed of three parts: (1) the elevation head, or water level above a datum; (2) the pressure head with reference to atmospheric pressure; and (3) the velocity head. Because ground water moves relatively slowly, velocity head can generally be ignored.

Porosity is the maximum amount of water a volume of geologic material can contain. Porosity depends on grain size, sorting, packing, and cementation. Porosity is expressed as the percentage of pore space (i.e., voids) contained in a total volume of material. For example, a porosity of 10 percent means that 10 percent of a volume of porous material is composed of voids. Typical aquifer porosities range from approximately 40 percent (e.g., well-sorted gravel deposits) to near zero in unfractured igneous rocks (Freeze and Cherry, 1979). Porosity, however, "does not indicate how much water the aquifer will yield" as it is not a measure of the size or inter-connectivity of the pores (Driscoll, 1986). For example, the porosity of clay may be higher than that of gravel, yet clays yield little water (see "specific yield" below). **Effective porosity** is the amount of interconnected voids in a material through which water or other liquids can travel divided by the total volume of material (Fetter, 1988). The size and shape of individual particles, how they are arranged relative to each other, and deposition of any cementing material determines the volume of interconnected void spaces. Fracture porosity is a measure of the void space caused by fracturing or dissolution of rocks. In crystalline (igneous) rocks, fractures may provide the only pore space. In porous rock, fractures provide porosity additional to inter-grain porosity.

The **grain-size distribution** of aquifers influences the porosity, effective porosity, and permeability of aquifers. Poorly sorted materials tend to have relatively low porosity because smaller particles fill voids between larger particles. Sediments that are well-sorted, such as dune sand deposits, tend to have high porosities and large water-holding capabilities.

Figure 5A
Calculation of Hydraulic Gradient in an Unconfined Aquifer



Structural geology factors can also influence the amount of void space in a formation and the ability of water to flow through an aquifer. Folds, fractures, and faults can control the presence and flow of ground water. Typically, fracture trends follow regional structural features such as folds or faults. The folding of rock formations, whether on a local or regional scale, can cause fracturing of geologic materials. Faulting of rocks can also create fractures adjacent to the fault. Fractures and faults may be filled with impermeable material, or they may act as conduits for ground water flow. Where fractures intersect in the subsurface, ground water may be plentiful. Fracture-trace analysis, the use of aerial photographs to locate surface manifestations of subsurface fractures, can provide an indication of successful well locations by identifying areas of intersecting fractures. Ground water flow through fractures in porous materials can be locally significant, as it is in recharge areas along subsidence-induced fractures in the alluvial valleys of the southwestern United States.

Hydraulic conductivity is a measure of the ability of a porous medium (or a fractured rock that approximates a porous medium) to transmit water or other liquid. It is expressed as the volume of water that will move in a unit time under a unit hydraulic gradient through a unit cross-sectional area of the medium. Hydraulic conductivity can be expressed in units of feet/day and can be derived from gallons per day (gpd)/unit cross-sectional area (square feet). The hydraulic conductivity of a particular porous medium is dependent on the size, distribution, and degree to which water-transmitting openings are connected, and the presence of joints, faults, and macropores. Although the nature of the ground water (e.g., temperature, contaminants) also affect hydraulic conductivity, for the purposes of conducting a resource assessment, these elements of hydraulic conductivity can generally be ignored. Most aquifers are heterogeneous, that is, hydraulic conductivity varies from point to point.

Transmissivity is a measure of an aquifer's ability to transmit water through a given saturated thickness. Transmissivity is the weighted average of horizontal hydraulic conductivities at various depths in the aquifer, multiplied by the saturated thickness of the aquifer (Nielsen, 1991). Transmissivity is expressed in terms of volume/time/length (area/time) of saturated thickness. Transmissivity is helpful in calculating flow rates and aquifer yield. The transmissivity of a typical sandstone aquifer may be less than 400 square feet/day to over 2,100 square feet/day, while the transmissivity of alluvial aquifers along stream beds can be more than 13,000 square feet/day (Robson, 1987). In practice, transmissivity of a formation is commonly measured whereas hydraulic conductivity is estimated from the transmissivity value or determined from slug tests. See Figure 5B (Heath, 1984) for an illustration of the difference between hydraulic conductivity and transmissivity.

For confined aquifers, **storativity** is defined as the volume of water that an aquifer releases from storage per unit surface area of the aquifer per unit decline in the component of hydraulic head normal to that surface (Freeze and Cherry, 1979). For unconfined aquifers, the term **specific yield** is used instead of storativity and is defined as the amount of water that a specific volume of saturated aquifer material will release by gravity drainage. Storativity and specific yield are dimensionless (unitless) quantities. Storativity values for confined aquifers (which range from 0.005 to 0.00005) are usually much lower than specific yield values for unconfined aquifers (which range from 0.01 to 0.30) (Freeze and Cherry, 1979).

Specific yield and specific retention are related hydraulic properties of an unconfined aquifer. The specific yield reveals how much water will drain due to gravity and can be expressed as the following (Fetter, 1988):

$$\frac{\text{volume of water a material will yield by gravity drainage}}{\text{total volume of the material}}$$

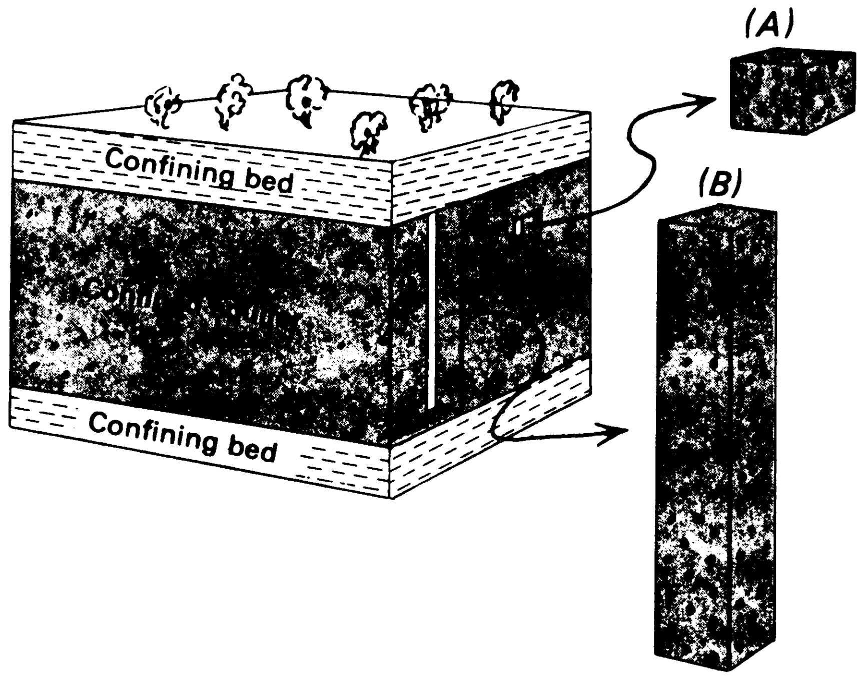
When water is drained by gravity, some of the water is retained by the material. Specific retention, the amount of water that is retained, can be expressed as the following ratio (Fetter, 1988):

$$\frac{\text{volume of water retained by the material}}{\text{total volume of the material}}$$

Clay materials typically exhibit high specific retention ratios, while sand and gravel typically exhibit high specific yield ratios.

The **velocity of ground water** flow in porous media and finely fractured media is generally low and is frequently measured at rates of feet/year. The macroscopic (i.e., average linear) velocity of flow under ideal hydrological conditions is equal to the discharge of a volume of water over a measured time (e.g., cubic feet/second) divided by the cross-sectional

Figure 5B
Difference Between Hydraulic Conductivity and Transmissivity



Hydraulic conductivity defines the water-transmitting capacity of a unit cube (*A*) of the aquifer. Transmissivity defines the water-transmitting capacity of a unit prism (*B*) of the aquifer.

Source: Heath, 1984

area of the flow divided by the volumetric porosity. Ground water velocity in porous media can be determined from the equation that is a form of Darcy's Law:

$$q = KI$$

where q = ground water velocity
K = hydraulic conductivity of the porous medium
I = hydraulic gradient

Calculated velocities are average values because K varies throughout most aquifers.

Ground water flow in finely fractured rocks that approximate porous media can be determined using the above equation. Flow of ground water in rocks with large diameter fractures and/or solution conduits, however, often cannot be calculated with this equation. Flow rates in such settings are often quite high; rates of one mile/day are not uncommon.

Methods

Data on hydraulic properties can be collected through a literature search of existing data and by using a combination of field and laboratory methods. Porosity is generally measured in the laboratory; transmissivity and storativity are generally calculated from data collected in the field. Hydraulic conductivity can be either measured or estimated in the laboratory or from field data. Laboratory measurements provide estimates of hydraulic conductivity at specific locations. Disturbance of the sample during collection and the nature of the laboratory equipment may cause errors in the estimation of hydraulic conductivity (and other hydraulic properties). Because hydraulic conductivity is dependent on geologic materials whose characteristics usually vary over relatively short distances, laboratory values frequently do not provide information applicable to broad areas. Field observations are generally more representative of the hydraulic conductivity throughout the aquifer. Values of hydraulic conductivity measured in the lab are often one to two orders of magnitude lower than field-measured values (Herzog and Morse, 1986).

A literature search may significantly reduce the time, effort, and cost required to adequately characterize hydraulic properties. It is important to identify existing local, regional, and national sources of hydrogeologic data. State geological surveys, the U.S. Geological Survey (USGS), and State natural resource regulatory and research agencies are excellent sources of hydrogeologic data and technical reports. U.S. Environmental Protection Agency (EPA) offices such as those that oversee the Resource Conservation and Recovery Act (RCRA), Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), Underground Storage Tank (UST), and Underground Injection Control (UIC) regulatory programs may require hydrogeologic data from permittees and petitioners that include information about hydraulic properties. Local regulatory agencies with responsibility for ground water protection will also collect and maintain hydrogeologic data. Other sources of data that should be considered include Federal agencies such as the U.S. Department of Agriculture's Soil Conservation Service (SCS), and private businesses that have conducted site characterization investigations.

Information obtained through a literature search may include well-log data and tables of hydraulic properties of geologic materials. Detailed reports and computerized data bases may also be available. Some data may be used directly in a resource assessment while other data can be used to derive various hydraulic properties. For example, descriptions of the grain size (e.g., sand, silt, clay) of porous media are recorded in drilling logs. Hydraulic conductivities can be estimated from these descriptions of texture using empirical relationships that have been developed for this purpose (Cartwright and Hensel, 1992; Freeze and Cherry, 1979). Porosity can also be estimated from these logs. An approximation of transmissivity can be estimated from specific capacity, which is a measure of the productivity of a well. Specific capacity is obtained by dividing the rate of well discharge by the drawdown of the water level in the well.

Field methods may be used to determine saturated hydraulic conductivity. Well tests (i.e., bail or slug tests) and aquifer tests may be used to collect water-level data over a period of time. Analytical methods can then be applied to these data to determine values of hydraulic conductivity, transmissivity, and storativity. Transmissivity and storativity can be estimated in the field from bail or slug tests, aquifer tests, and tracer tests. In addition, borehole geophysical methods may be used to estimate hydraulic conductivity.

Bail tests involve the removal of a known volume of water from a single well and careful measurement of the subsequent recovery of the water level over time (Nielsen, 1991). Slug tests measure the water level decline in a well over time after a measured amount of water has been added to a well (or a slug used to displace water is placed in the well)

(Freeze and Cherry, 1979). Analytical methods can be applied to these data to estimate the hydraulic conductivity of the aquifer. Horizontal hydraulic conductivity is measured as water travels horizontally to or from the well through the aquifer; the vertical component of flow from adjoining confining layers and from within the aquifer is a function of the vertical hydraulic conductivity of the aquifer or confining layer.

Aquifer tests are a field method for determining transmissivity and storativity of porous media (and in finely-fractured rocks that approximate porous media). An aquifer test is performed by pumping a well at a constant rate over a period of time ranging from several hours to several days and measuring the change in water level in observation wells or piezometers located at different distances from the pumping well. Time versus water-level-drawdown data are then interpreted using graphical and analytical methods. The hydraulic conductivity can be estimated from these data if the thickness of the confined aquifer or saturated zone of an unconfined aquifer are known. Two common methods are used to analyze the data to determine transmissivity and storativity. The Theis method involves curve matching on a log-log plot while the Jabob method interprets the data with a semi-log plot (Freeze and Cherry, 1979; Walton, 1962).

Tracer tests can be used to estimate the degree of hydraulic connection along potential flow conduits, such as fractures or solution channels in non-porous media, and can be used to estimate average flow velocities in porous media. In this field method, a tracer (e.g., a salt, radioactive isotope, or fluorescent dye) is added to the ground water reservoir; monitoring piezometers or wells are used to determine the increase in the concentration of the tracer over time at selected monitoring locations (Freeze and Cherry, 1979). Tracer tests can also measure arrival times of ground water at points known to be in hydraulic connection with the tracer-source site.

Geophysical methods for determining hydraulic properties may involve surface or subsurface investigations. Borehole geophysical data can be used to identify areas in the stratigraphic section where high porosity and permeability rocks (i.e., rocks with high potential yield) occur. Several types of logs, including resistivity, spontaneous potential, neutron, and gamma, provide detailed information about the subsurface. Effective porosity can be determined from calibrated log-normal resistivity logs; permeability can be estimated from porosity and injectivity data (Fetter, 1988).

Laboratory measurements of hydraulic properties of geologic materials rely on samples taken in the field and transported to the laboratory. These samples must be carefully collected and maintained to minimize disturbance of the material. Porosity, hydraulic conductivity, and grain-size distribution can all be determined from laboratory measurement of samples.

Porosity is generally measured in the laboratory by obtaining values for the oven dried mass of the sample, field volume, and solid particular volume (see Freeze and Cherry, 1979). Another method used in laboratories for determining porosity is the gas pycnometer method. The gas pycnometer method measures gas-filled volumes in porous media based on the volume-pressure relationships of gasses.

Laboratory methods for determining hydraulic conductivity include direct measurement methods using constant- or falling-head permeameters or indirect estimates using particle-size analyses of material. The direct methods involve measuring the volume of water that flows through a fixed cross-section of saturated porous media under an applied hydraulic gradient. These methods use many types of devices in which flow may be directed either up or down through the core sample, the hydraulic gradient may be high or low, and the hydraulic head may be constant or falling (Fetter, 1988).

Particle-size analysis of drilling-core samples supplies information on the size distribution of the particles that comprise unconsolidated porous media. As previously described, hydraulic conductivities can be estimated from textural information using established empirical relationships. Using laboratory determinations of grain-size distributions from drilling cores, however, is preferable to textures (grain size) recorded in well logs, because textures noted in well logs are usually determined from subjective visual estimates and "feel" tests.

Presentation of Data/Information

Information on hydraulic properties may be most easily understood and interpreted when presented in maps, charts, or figures. Maps are useful to show the areal distribution of hydraulic properties within a hydrogeologic unit. If the area to be mapped contains significant variation in hydraulic properties, a large amount of data may be needed to adequately describe the hydraulic characteristics of the area.

Charts or figures may show such information as the depth and thickness of hydrogeologic units. Data presented in tables or data bases may be useful for modeling the hydrogeologic setting.

If data are digitized, a Geographic Information Systems (GIS) may be used to assist ground water scientists by producing initial drafts of maps of hydraulic parameters. Maps may be overlain (manually or with use of a GIS) to develop derivative maps. Mapping software for personal computers is also available to assist in the preparation of simple maps. It is important to recognize, however, that professional expertise and judgement are necessary in the development of any maps of hydraulic properties.

Considerations

The collection and interpretation of hydraulic data will assist resource managers in evaluating the quality and quantity of ground water within their jurisdiction. The results of this collection and interpretation of data will often depend on the resources available to perform the study, the methods used, and the selection of study areas or sites. The data collection process should be organized to meet the objectives of the study and provide the best use of available resources.

Adequate assessment of hydraulic properties for a hydrogeologic setting requires a substantial amount of data. Collection of large amounts of data may be very costly, especially if new wells must be installed. Therefore, it is especially important to first conduct a literature search first to determine and locate existing hydrogeologic data.

Data to determine aquifer characteristics may be collected from "point"-type tests (slug or bail) and/or aquifer tests. In general, slug or bail tests provide information for a specific point, while aquifer tests provide generalizations across the area of influence of the pumping well. Managers should be aware that water pumped during an aquifer test must be diverted to surface waters or a collection area and that discharge permits may be required. Managing the pumped water can be especially difficult and costly if the pumped water is contaminated.

Sites for data collection activities must be chosen carefully to maximize the applicability of the new data. New data collection sites should be selected only after considering all presently available hydrogeologic information. If aquifer tests are planned, it is necessary to ensure that the screened intervals of the pumping and monitoring wells are in the same hydrogeologic unit. A reliable stratigraphic framework, as described in Components #1 and #2, will help determine which tests should be conducted and which data should be collected.

When using historical data, it is important to consider the accuracy and reliability of the information. This can be accomplished by examining what types of methods were used to collect the data and the expertise in the organization that collected them.

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Component #5: Confinement and Interaction Between Aquifers

Definition

Confined aquifers are located between confining layers, or aquitards, that impede the vertical flow of ground water. Aquitards are geologic formations with significantly lower hydraulic conductivity than aquifers. Examples of aquitards include unfractured shale and siltstone. Natural interaction between aquifers occurs when aquitards are absent or permeable enough to transmit some ground water to underlying or overlying aquifer units. The movement of water through ground water systems is controlled by vertical and horizontal hydraulic conductivity, thickness of the aquifers, thickness and degree of continuity of confining beds, and the hydraulic gradient. The degree of hydraulic connection between aquifers and aquitards is primarily a function of the hydraulic properties of the aquitard and the vertical hydraulic gradients as shown in Figure 6 (Heath, 1989).

Objective

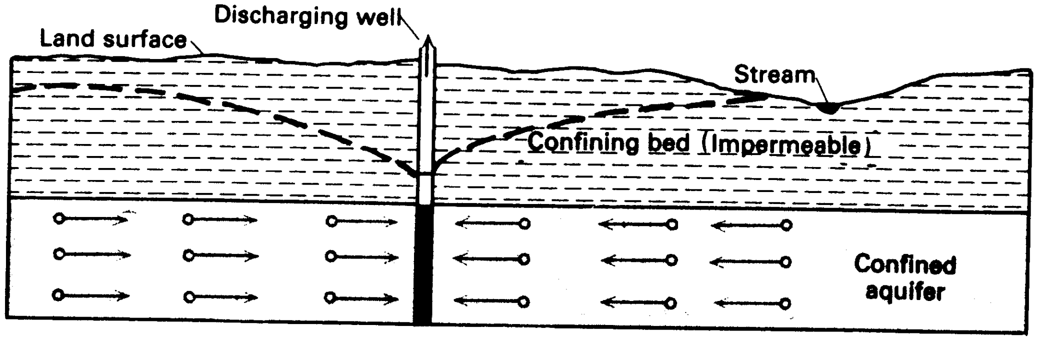
The objective of analyzing the degree of interaction between aquifers is to determine the quantity of water that is flowing through the confining layer to the aquifer, both under natural conditions and as a result of well discharge. Knowledge of relative confinement and/or interconnection between aquifers is essential to siting water supply wells and well fields, and assessing the vulnerability of deeper ground water to sources of surface contamination. Interconnection of aquifers often complicates efforts for siting waste disposal facilities or locating potable water supplies.

Data Needs

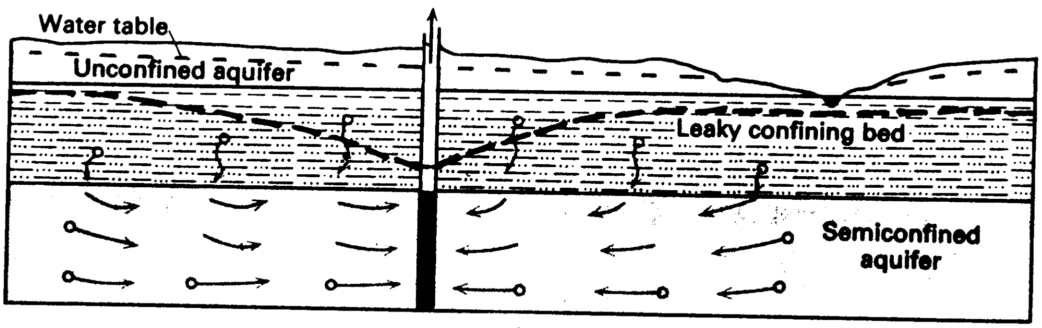
To achieve the objectives of this Component the following data should be collected:

- lithology and stratigraphy
- geophysical properties

Figure 6
Different Conditions of Aquifer Confinement and Interaction



(a)



(b)

Source: Heath, 1989

- hydraulic properties
- water quality

Freeze and Cherry (1979) define aquitards as those layers in a stratigraphic sequence that have insufficient permeability to allow wells completed in them to yield an economically significant amount of water. Although water flows very slowly within aquitards, their capacity to store ground water can be quite high (Driscoll, 1986). Thus, the permeability of aquitards (confining layers) and the degree to which they allow flow or leakage of ground water between aquifers vary according to the aquitards' **lithology, stratigraphy,** and **hydraulic properties**. Knowledge of these attributes of the confining layer(s) leads to a better understanding of the aquifer and aquitard relationship and can assist in identifying highly confined areas and areas where the greatest potential for aquifer interaction may occur. See Figure 6 for an illustration of this concept. Figure 6a depicts horizontal flow to a well discharging from a confined aquifer. Figure 6b depicts leakage from an upper, unconfined aquifer into a confined aquifer from which a well is withdrawing water.

Confining layers between aquifers impede the exchange of water and contaminants; the thicker the confining layer (or lower the permeability) the greater the impedance. Similarly, a thicker confining layer (or lower permeability) above a shallow confined aquifer, reduces susceptibility of the aquifer to surface contamination. Thickness, permeability, lithology, and hydraulic conductivity of confining layers may vary within short distances. Fractures, higher permeability zones, and man-induced breaches such as boreholes are conduits between aquifers. Over large distances, confining layers may disappear completely as a result of environmental conditions at the time of their deposition.

Geophysical data can be used to determine the extent of confining layers and permeabilities of geologic materials. **Hydraulic property** data, such as hydraulic conductivity of aquifers and aquitards, storativity, and hydraulic gradient, combined with information on continuity of the aquitard and the presence of artificial penetrations (e.g., boreholes and poorly constructed wells), assist in the determination of aquifer confinement and interaction.

Vertical leakage occurs through most confining layers; that is, they are not "tight". According to Meinzer (1942), a well pumping from a confined aquifer (except one overlain by a very impermeable layer) receives water from four major sources:

(1) water moving through the aquifer toward the well

(2) water forced from the aquifer by compaction due to the weight of overlying materials

(3) the expansion of water in the aquifer as its pressure decreases due to pumping

(4) water that is forced from surrounding aquitards by compaction

Over time, a significant portion of water pumped from a confined aquifer may originate as "leakage" from overlying and/or underlying aquitards.

Water quality is an important factor in determining the presence and nature of interconnection between aquifers. Similar water quality in adjacent aquifers is often an indication of good hydraulic connection. Water of different qualities frequently indicates poor connection. Information on the geochemistry, presence and type of radionuclides and even contaminants in ground water from each aquifer can be used to help determine the presence or absence of inter-aquifer flow. A comparison of water temperatures may also provide information regarding hydraulic connection.

Methods

Data on hydraulic properties of aquifers and aquitards can be collected through a search of existing data and by using a combination of laboratory and field methods. For more information about analytical methods to determine hydraulic properties of aquifers, see Component #4. Application of analytical methods to aquifer-test data can be used to determine the effects of leakage from aquitards to the water pumped from an aquifer and to the recovery of water levels in the aquifer after pumping (Kruseman and De Ridder, 1990).

Geophysical methods of determining hydraulic properties may involve surface or subsurface investigations. Borehole geophysical data can be used to interpret areas in the stratigraphic column where low-permeability rocks (those rocks that limit aquifer interaction) occur. Several types of logs, including resistivity, spontaneous potential, neutron, and gamma logs provide detailed information concerning the subsurface. Comparison of geophysical data from different well-logging sites assists in the determination of the presence and position of confining units.

Confining layers often contain areas of higher permeability or man-made breaches, that permit significant ground water flow to the underlying aquifer. This flow can be estimated from the saturated thickness and hydraulic conductivity of the aquifer and the hydraulic resistance of the confining layer (Kruseman and De Ridder, 1990). Hydraulic resistance of an aquitard is the ratio of its saturated thickness to its vertical hydraulic conductivity. High values indicate large resistance to upward or downward leakage.

Finally, geochemical methods can also be used to determine interaction between aquifers. An understanding of the overall geochemistry of water, including the absence or presence of common constituents, can assist in characterizing the degree of aquifer interconnection. See Components #9 and #10 for more information about the geochemical characterization of ground water.

Presentation of Data/Information

Information on geologic materials, as it relates to the confinement and interaction of aquifers, may be presented in table or chart form to show the depth and thickness of aquifers and aquitards and their associated hydraulic data. Geologic cross-sections depict a geologist's or ground water scientist's interpretation of aquifer-aquitard relationships that improve understanding of the interconnections between aquifers. Maps displaying the thickness (isopach maps) and extent of aquifers and aquitards are typically used to present such information. Components #1 and #2 discuss the use of maps in more detail.

Graphical displays and maps showing areas of high aquifer interconnection or confinement are often produced from site-specific data. Geographic Information Systems (GIS) may be used to assist ground water scientists by producing initial estimates of aquifer and aquitard attributes such as potentiometric surface elevation, hydraulic conductivity, transmissivity, composition, and unit thickness. The maps developed may be manually overlain to allow the creation of derivative maps of relative aquifer connection or relative aquifer confinement. If the maps developed are digitized as separate coverages, a GIS may be used to superimpose the map layers and aid in the development of derivative maps.

However, it is important to recognize that professional expertise and judgement are necessary in the development of any maps that interpret aquifer data.

Considerations

All available hydrogeologic data should be considered when determining the degree and lateral extent of aquifer interaction across a region. To properly interpret this data, a ground water scientist should have a good understanding of the nature of the hydrogeologic setting (see Components #1 and #2) and be cautious when correlating site-specific information across the region.

Aquifer-test and drilling-core data are helpful in the determination of properties needed to assess the confinement and interaction of aquifers. These data may exist in local or State government offices. If few data are available, field investigations, including the installation of pumping wells and piezometers, may be needed to collect the necessary information. Such data collection could prove to be costly. Geophysical investigations may reduce costs and rapidly provide data on some subsurface characteristics but the data may be difficult to interpret.

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Component #6: Ground Water Recharge and Discharge Characterization

Definition

Ground water recharge and discharge are components of the hydrologic cycle. Recharge is the water that enters the ground water reservoir; discharge is the water that exits. Characterizing recharge and discharge includes identifying their rates and areas of occurrence.

Objective

The objectives of characterizing ground water recharge and discharge are: (1) to protect recharge areas from contamination, (2) to gain knowledge about changes in ground water levels, and (3) to gain insight into the nature of the impact of ground water on the quality of the surface water resources into which ground water discharges, the flow of streams, and the size of lakes.

It is important to recognize that *ground water* recharge and discharge are processes that are separate from, but related to, *aquifer* recharge and discharge. For example, in hydrogeologic settings with deep confined aquifers, only a small fraction of ground water recharge may contribute to the recharge of a specific aquifer of interest. The remaining recharge may be discharged to local surface water bodies or be intercepted by shallower, overlying aquifers.

Data Needs

The data needed to characterize ground water recharge and discharge in a resource area are:

- location of recharge and discharge areas
- recharge and discharge rates
- precipitation
- geologic and soils data
- water levels from wells completed in area aquifers and confining units
- interaction of ground water with surface water

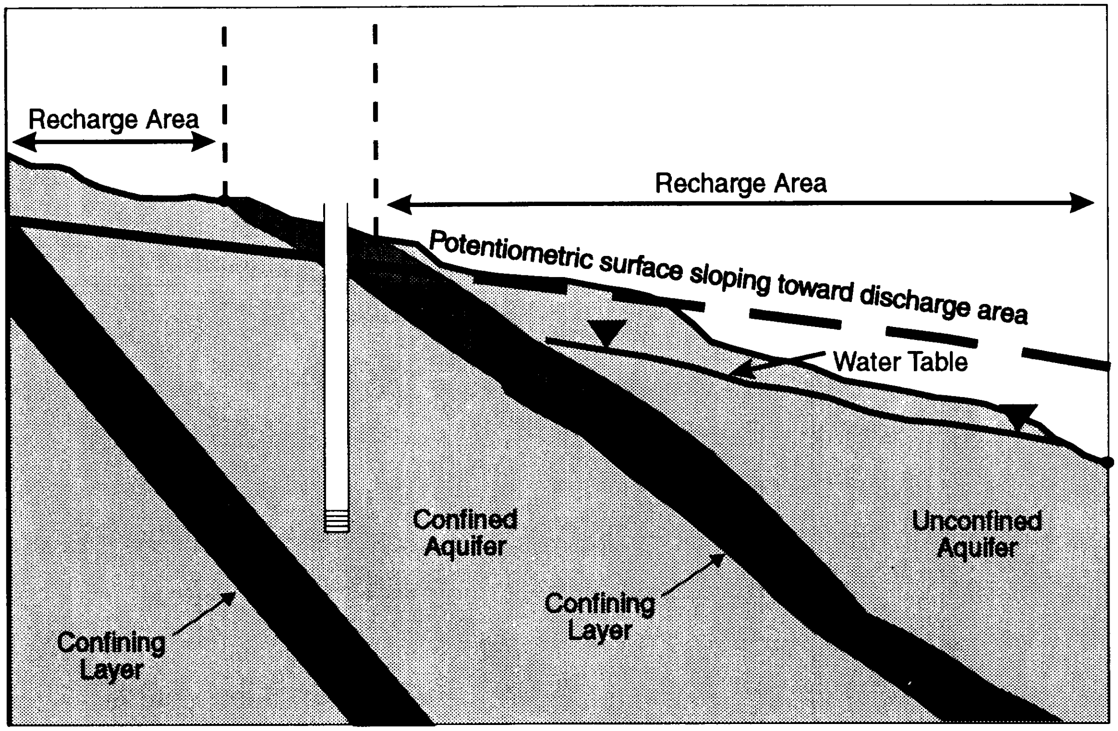
Recharge and discharge areas are the ground surface areas in which water enters or exits the ground water system. Ground water flow in a recharge area is downward; ground water flow in a discharge area is upward. Figures 7A and 7B (Baldwin, 1963; Heath, 1989) present a basic depiction of recharge and discharge characteristics. From the recharge area, the water moves through the ground water reservoir and exits (perhaps after flowing through more than one aquifer) through a discharge area, such as a spring, a seep, or surface water body. Ground water in recharge areas is usually more susceptible to surficial contamination than in other areas. Contaminants entering through the recharge area may exit through the discharge area. Thus, the locations of recharge and discharge are essential to a thorough understanding of the hydrologic cycle and the routes for contamination.

For some purposes, such as the development of management priorities, it may be important for a State or local authority to distinguish between recharge to, and discharge from, a ground water reservoir. Recharge or discharge at a given geographic location may not be to or from a particular aquifer of interest. In some settings, little or no local ground water recharge and/or discharge may be to or from the locally-used aquifer.

Recharge and discharge rates are affected by a number of factors, including the duration and quantity of precipitation events, the duration and quantity of irrigation, surface evaporation, soil moisture content, soil infiltration rates, hydraulic conductivity of geologic materials, vegetative cover, water demand of plants, land use, depth of the water table, and distance and direction to a stream or river (Walton, 1965). Recharge and discharge are generally estimated as annual average rates and for the ground water reservoir as a whole.

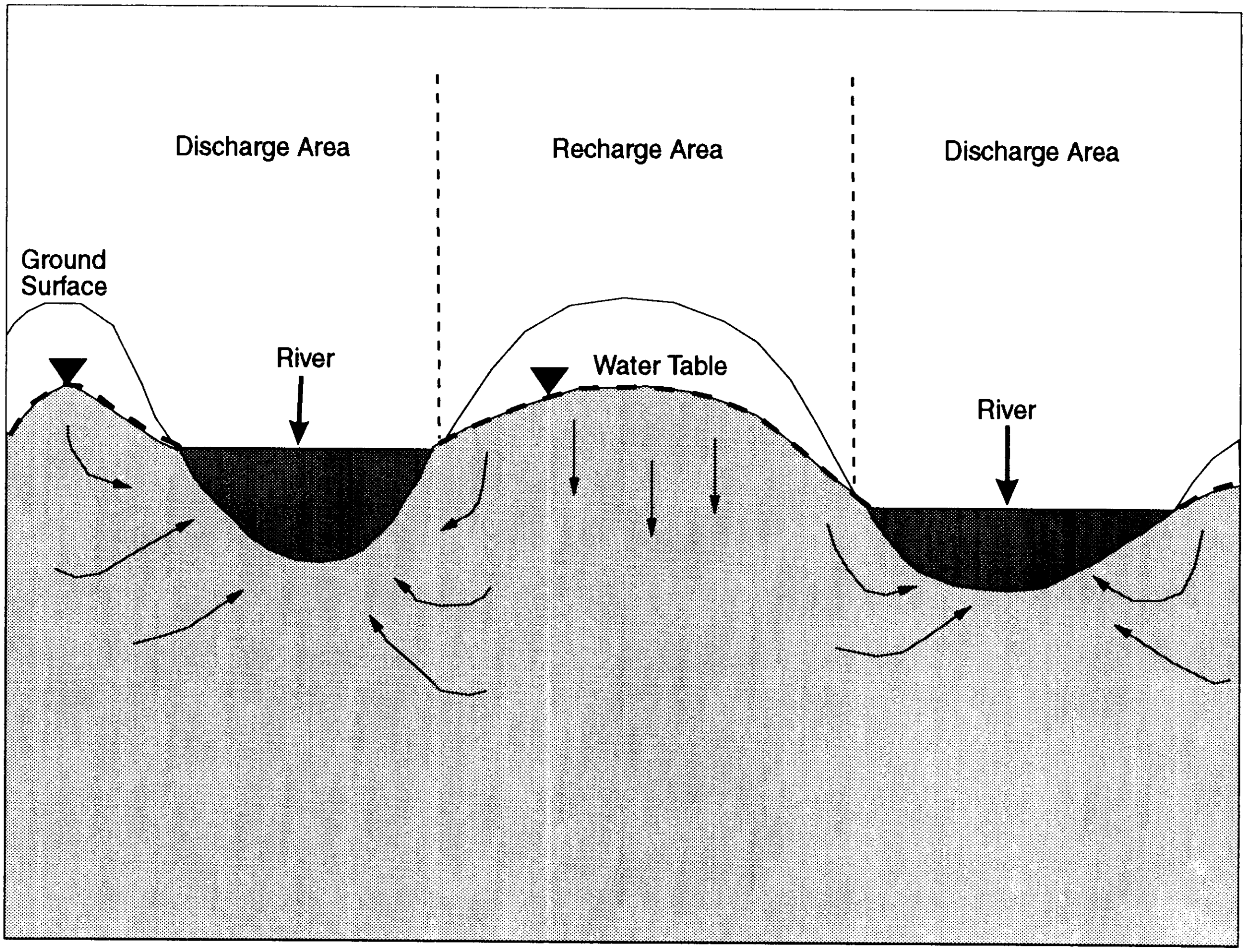
Precipitation is often thought of as the first step in the hydrologic cycle. Rainfall and snowmelt that does not run off, evaporate, or transpire from plants, infiltrates the soil and unsaturated zone and recharges the subsurface hydrogeological systems. Although the

Figure 7A
Recharge Areas for a Confined and Unconfined Aquifer



Source: After Baldwin, 1963

Figure 7B
Ground Water Recharge and Discharge Areas



Source: After Heath, 1989

annual recharge rate is directly related to the annual precipitation rate, recharge is usually less than precipitation because not all precipitation infiltrates the soil.

Geologic and soils data, are important in locating recharge and discharge areas and in estimating recharge and discharge rates. Of particular importance are data on the infiltration rates of soils, and the hydraulic conductivity and stratigraphy of the unsaturated zone. Low-conductivity layers in the unsaturated zone may laterally deflect, or prevent the recharge of, precipitation. Unconfined aquifers generally receive significant recharge from direct percolation of precipitation into the aquifer. Confined aquifers, however, are usually separated from the surface by relatively impermeable strata (See Figure 7A, Baldwin, 1963). Recharge areas for confined aquifers may be some distance from the area of confinement. Recharge to the confined area is primarily from lateral flow within the aquifer, although some recharge is from vertical flow through confining layers. For more information on the types of data needed to characterize geologic materials and aquifer confinement, see Components #1, #4, and #5.

Because ground water flows from higher water level to lower water level, a comparison of water levels from closely spaced wells, installed at different depths, provides the direction of vertical flow. Upward flow indicates discharge area, downward flow, recharge areas.

Little ground water enters an aquifer where it is confined. Although some leakage through the confining bed often occurs, confined areas are usually not considered to be either recharge or discharge areas.

The principle governing ground water flow to or from a stream is the same as that described above. If the elevation of the water surface of a stream is lower than the elevation of the water level in a well screened either in the stream-bed sediments or in the ground water below, then the stream is gaining water from the ground water reservoir and vice versa.

Interaction with surface water should also be considered in characterizing recharge and discharge. Streams and wetlands are usually ground water discharge areas; however, these surface features may also recharge aquifers depending on surrounding geology and hydraulic and climatic conditions. Lakes frequently have recharge and discharge areas along their length. The location of surface waters and their impact on ground water are, therefore, important in determining overall recharge and discharge characteristics. For more information on the types of data needed to assess ground water and surface water interaction, see Component #7.

Methods

Methods employed to characterize ground water recharge and discharge include literature searches and field methods. Frequently, information characterizing recharge and discharge for a study area may already exist. Some data are easily obtainable. For example, precipitation data are available from the National Oceanic and Atmospheric Administration (NOAA). Soil survey information describing the upper 60 inches of material for most counties in the United States is available from the U.S. Department of Agriculture, Soil Conservation Service (SCS). SCS soil survey maps are often updated and maintained by local county soil scientists or agricultural extension offices. Geologic information is available from the U.S. Geological Survey (USGS) or State geological surveys.

One can often identify potential recharge and discharge areas based on a few factors, such as the composition and areal distribution of geologic materials, on relevant water-level data and/or infiltration rates. Where available, aerial photographs and satellite imagery, particularly near infrared imagery, can provide insight into the location of ground water discharge areas. For example, Keefer and Berg (1990) produced a map of potential aquifer recharge areas in the State of Illinois by evaluating depth to the aquifer, the occurrence of major aquifers, and the potential infiltration rate of the surficial soil materials. Computerized Geographic Information Systems (GIS) may be useful in performing this type of analysis.

The data required to perform recharge and discharge analyses may be available from the existing sources described above, or obtained through field methods that provide more precise, site-specific information. For example, surface geophysical methods, such as seismic reflection or refraction, electromagnetics, ground-penetrating radar, and electrical resistivity/conductivity may be applied to a study area to examine the subsurface geology. Similarly, well logs, core samples, test holes, and borehole geophysical logging provide information about the soils, geology, and water level at a point of interest. The data may be expanded to cover a study area by sampling at several selected points and correlating the data. Monitoring wells, installed in clusters (i.e., groups of wells screened at various depths in aquifers), can provide valuable information on the vertical component of ground water flow within geologic deposits. The American Society for Testing and Materials (ASTM) publishes methods for obtaining geologic data and applying them to ground water recharge mapping (Andres, 1991).

The introduction of manmade tracers or use of natural tracers may aid in evaluating and identifying recharge and discharge areas. For example, a tracer may be injected into an aquifer to determine the flow rates within the aquifer and where the aquifer discharges into a stream. Tracers may also be used to locate areas of ground water recharge from surface water sources.

Recording and non-recording rain gauges can measure precipitation and provide information on precipitation quantity and duration. Numerical estimates of average ground water recharge rates begin with an analysis of precipitation data, and are developed either through a flow-net analysis, a hydrologic budget, or use of a computer model.

Presentation of Data/Information

Recharge and discharge areas are usually displayed using two-dimensional maps. Three-dimensional representations or figures showing recharge from and discharge to aquifers or surface waters may also be useful in more detailed, site-specific studies. Relative rankings of potential recharge rates or estimates of actual recharge rates can also be shown on maps. If substantial amounts of data are available, a GIS may be useful to manage the information (if digitized) and assist ground water scientists in developing initial drafts of recharge and discharge maps. If numerical estimates of recharge rates are available, it may also be beneficial to present this information in tables or in graphs, which are better suited to displaying seasonal changes.

Considerations

Identifying recharge areas allows environmental planners to focus attention on areas that may be particularly susceptible to contamination. Armed with information about recharge areas, managers and planners may choose to provide more protection for these critical areas rather than implement uniform protection policies across much larger areas.

In terms of scale, recharge and discharge have been characterized for areas ranging in size from individual counties (Berg, Kempton, and Stecyk, 1984) to sections of States (Rehm, Groenewold, and Peterson, 1982; Andres, 1991) to entire States (Keefer and Berg, 1990). Quantitative estimates of recharge and discharge are available in some cases, such as Walton (1965) and O'Hearn and Gibb (1980). The resources required to characterize recharge and discharge vary depending on the scale of the study, the level of detail required, and the availability of existing information.

Using existing studies and maps to locate recharge and discharge areas requires some effort; determining recharge and discharge rates is more difficult. Evaluation of ground water recharge rates requires fairly detailed subsurface information. Use of a GIS may simplify the process of assembling, storing, and managing georeferenced information and may assist ground water scientists in developing initial maps if the data are available in digital format. However, the costs of computer systems and staff time required to set up and maintain a GIS, if one is not already available, can be significant. Mapping packages available for personal computers can assist in developing simple maps.

If sufficient information does not exist for the study area, additional data collection will probably be necessary. Data collection may include test-hole drilling and logging, log interpretation, and water-level measurement and interpretation. Geophysical techniques provide additional information but require sophisticated equipment and may be difficult to conduct. Surface geophysical investigations can be performed rapidly but provide data that are difficult to interpret. Tracer methods also have substantial labor and equipment demands, although interpretation is much simpler. The presence of isotopes or other naturally occurring tracers in ground water may reduce the costs of conducting tracer tests.

Estimation of actual ground water recharge rates generally requires existing field data to be supplemented with additional information. Flow-net analysis is based on water-level data and estimates of the hydraulic conductivity of the near-surface geologic formations. If flow nets have not been constructed, information on the hydraulic head at various locations and water-level depths throughout the study area should be collected and compiled. The hydraulic conductivity of the surficial materials may be determined from actual measurements, estimated from samples obtained from drilling cores or cuttings from test holes, or estimated from geophysical data and well logs.

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Component #7: Ground Water and Surface Water Interaction

Definition

Ground water and surface water interaction refers to the movement of water between a geologic unit and a surface water body. The volume and direction of that movement will vary with time and geologic setting.

Objective

The objective of assessing ground water and surface water interaction is to determine the qualitative and quantitative impacts of surface water and ground water on each other and any potential human health and ecological impacts that may result. In some hydrogeologic settings, it is necessary to assess shallow ground water and surface water as a single system, because of the high degree of interaction between the two.

Data Needs

The data needed to assess ground water and surface water interaction are:

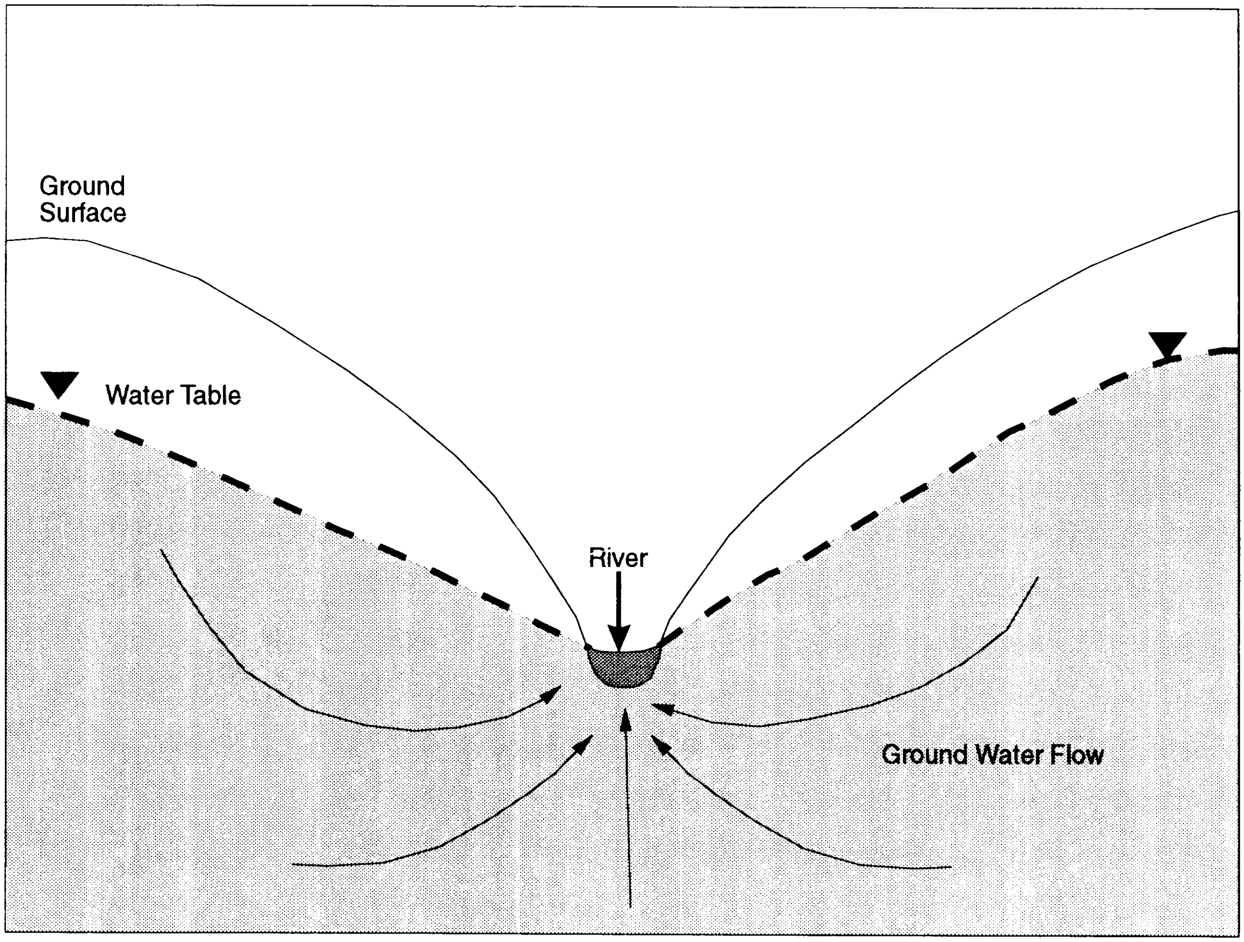
- surface water and ground water hydrology (i.e., direction, quantity, and rate of flow)
- hydraulic properties, lithology, and mineralogy of geologic materials
- surface water and ground water quality
- ecological data (both for ground water and surface water)
- sediment quality and type
- precipitation and temporal changes

Surface water and ground water hydrology control the extent of ground water and surface water interaction. The specific parameters of importance are direction of flow (from ground water to surface water or vice versa), and rate and quantity of flow between ground and surface water. These characteristics help determine the impact of surface water on the quality and supply of ground water, and vice versa. Information on the boundaries of surface water features such as rivers, streams, and wetlands, areas of ground water interaction with surface water, and hydraulic connections is also necessary to completely understand surface and ground water hydrology.

The U.S. Geological Survey (USGS) estimates that 40 percent of average annual streamflow in the United States is derived from ground water (Moody, 1988). The interaction of ground water and surface water, however, is not limited to ground water discharges to surface water; surface water can also infiltrate to recharge the ground water reservoir. When ground and surface waters are hydraulically connected, a change in the water level of either affects the other. For example, during the beginning of dry periods that follow periods of extended rainfall, streamflow may decrease substantially while the water table adjacent to the stream may remain high allowing ground water discharges to the stream, adding to its flow. After prolonged dry periods, both the stream and the water table would be low. Analogously, following large or successive rainfall events, stream levels may rise more rapidly than ground water levels, causing streamflow to enter the stream's banks. Figures 8a and 8b illustrate the interaction between ground water and surface water (Heath, 1989). Human-induced impacts may also affect the ground water/surface water relation. In a situation similar to that shown in Figure 8b, Barari and others (1993) reported that the loss of water from a river to an aquifer, due to pumping of municipal wells, was so great in 1988 that the river ceased flowing in the vicinity of the municipal wellfield.

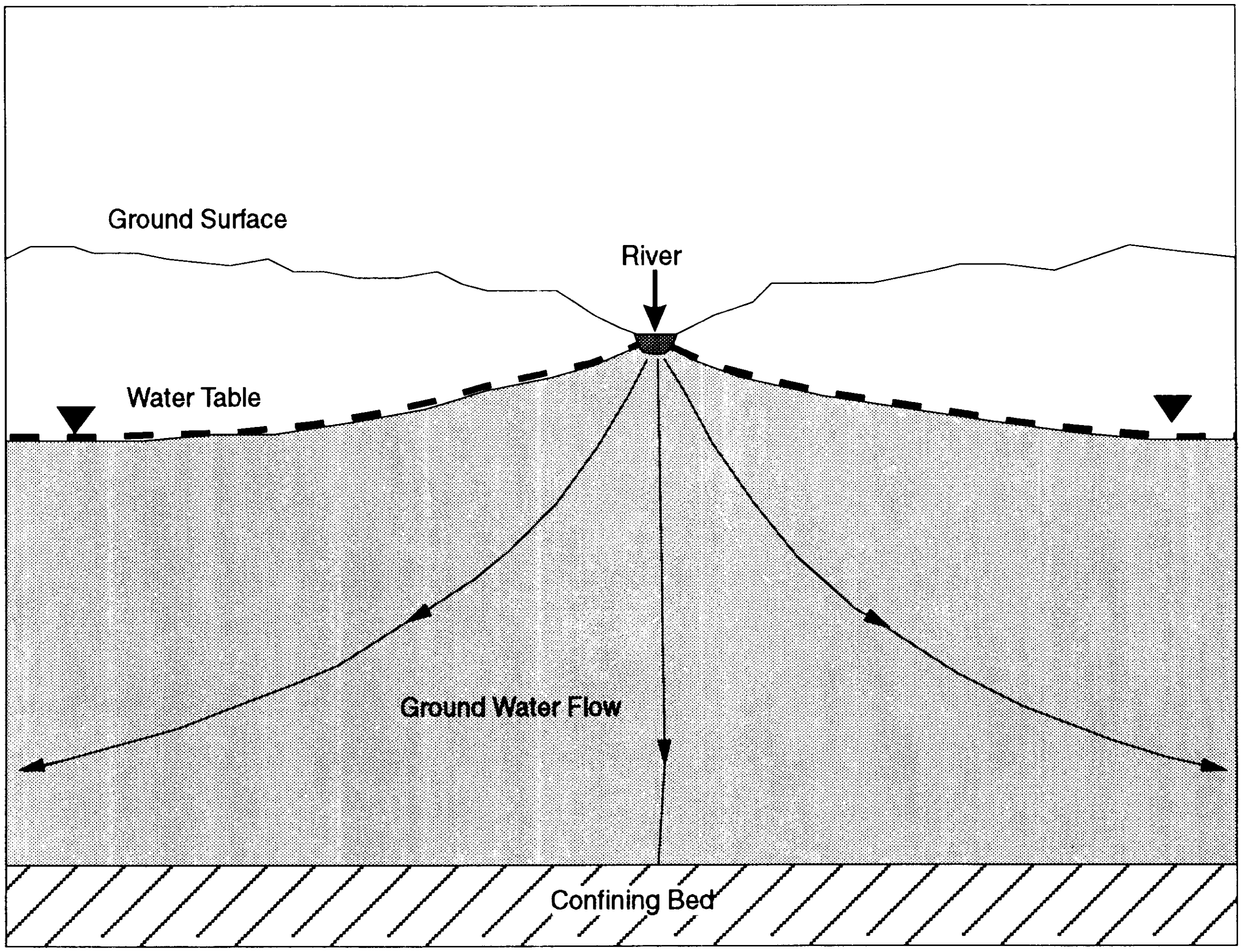
Ground water/surface water interactions can also be significant in areas where lakes occur. Some wetlands may obtain a substantial portion of their water from ground water. The hydrologic behavior of lakes is often strongly influenced by the ground water flow system underlying them (Freeze and Cherry, 1979). Furthermore, interaction with underlying ground water can be an important factor in determining the water budget of a lake. Lakes that have well-defined inflowing and outflowing streams receive most of their water from surface water contribution, while other lakes receive most of their water from discharges of underlying ground water (Fetter, 1988). The degree and type of interaction between lakes and ground water flow systems primarily depend on factors such as: the relative water level in each, the nature of the sediments underlying the lake, and climate. In general, large lakes are typically areas of net discharge of regional ground water systems (i.e., net water flows from the ground

Figure 8A
Cross Section Showing Ground Water Discharging to Surface Water



Source: After Baldwin, 1963

Figure 8B
Cross Section Showing Surface Water Recharging to Ground Water



Source: After Heath, 1989

water system to the lake), and small lakes in the upper portions of watersheds are usually areas of net recharge for local ground water flow systems (Freeze and Cherry, 1979).

The **hydraulic properties, lithology, and mineralogy** of geologic units affect the direction, quantity and quality of flow between ground water and surface water. The hydraulic properties (e.g., hydraulic conductivity and porosity) of the geologic materials that comprise the saturated and unsaturated zones influence the rate of interchange between ground water and surface water (Soller and Berg, 1992). These hydraulic properties are a function, in part, of lithology. The mineralogy of geologic units also affects water quality. For example, ground water from calcareous aquifer materials that discharges to surface water may increase surface water alkalinity. For more information on the types of data needed to characterize the hydraulic properties of geologic units, see Component #4.

Information on the **water quality** of ground water and surface water is important in understanding how ground water and surface water affect each other. For example, water-quality data have been used to determine the flow between surface and ground water (e.g., in a 1991 study of aquifers in the Nashua River Basin in Massachusetts) by deducing the extent of the interchange of water from an analysis of the quality of two water bodies (USEPA, 1992). Water-quality data could include information on the presence and concentration of natural constituents, radionuclides, manmade contaminants, temperature, and pH. For more information on the types of data needed to assess ground water quality, see Component #10.

Ecological data may include inventories of: microorganisms, plants, animals, and insects (e.g., measurements of the population or the relative abundance of various species). For the purposes of determining ground water/surface water interaction, ecological data of interest are those data related to the biota in and overlying the zone of interchange. These ecological data may help define the boundaries of this zone, can be used as an indicator of the ecological health of ecosystems and, indirectly, provide ground and surface water quality information.

Sediment quality and type are factors affecting surface water quality, and, therefore, may affect ground water quality through the interaction of surface and ground water resources. Individual sediment particles, suspended in surface water or settled on stream and lake bottoms, can carry thousands of molecules of pesticides, organic wastes, and other chemicals (U.S. Department of Agriculture, 1989). Some organic chemical constituents of ground water may also be adsorbed onto channel sediments. Fine-grained sediments that accumulate on lake and stream bottoms create low-permeability layers that decrease the rate of interchange between ground water and surface water. Positive correlations between ground water chemistry and stream sediment chemistry may indicate interchange.

Knowledge of **precipitation and resulting temporal changes** are critical in assessing surface and ground water interaction. Precipitation is directly or indirectly, the source of ground and surface water recharge. As such, precipitation directly impacts ground and surface water levels and quality. The transport of contaminants and contaminated sediments by overland flow to streams impacts surface water quality. Surface water infiltration can transport these contaminants into the ground water. Temporal changes, due in large part to seasonal fluctuations in precipitation or climate, but also to daily fluctuations such as tidal cycles, may impact the relation between ground and surface water levels, and thus affect the direction, quantity and quality of interaction. For example, as discussed earlier, seasonal fluctuations in hydrological and meteorological conditions can result in cyclical variation in exchanges of water. Understanding temporal variations is helpful for a comprehensive assessment of the interaction of ground water and surface water.

Methods

A number of methods can be used to assess the extent of ground water and surface water interaction. These methods include:

- literature search
- geological characterization
- direct field measurement
- indicator studies
- hydrograph separation
- numerical flow models

Some information on ground water and surface water interaction for any given area may already exist. Therefore, a search of available literature is advisable. The literature search should include both published and unpublished materials, such as maps, reports, and monographs. Some types of data, including information on geologic units and climate (e.g., precipitation), may be available from sources, such as the USGS, the U.S. Department of Agriculture, or the National Oceanic and Atmospheric Administration (NOAA). Federal, State, and local agencies with responsibility for ground water or surface water protection may have additional information. Where available, aerial and satellite imagery may provide cost-effective information on the locations of areas of ground water/surface water interaction.

Other methods exist for obtaining data. The magnitude of ground water and surface water flow at specific points can be determined in the field with equipment such as seepage meters and piezometers. These devices are inserted into and/or through the sediments of a lake or stream or along a profile from uplands through a stream. The instruments may provide a rough estimate of ground water/surface water exchange. There are, however, numerous field-related problems associated with the use and collection of reliable data with these devices. Data collected from these devices, from observation wells, or from water table contour maps, along with estimates of the hydraulic conductivity and the cross-sectional area of the aquifer that is hydraulically connected to a stream, can form the basis for ground water flow measurement. Applying Darcy's Law to this information can provide an estimate of the ground water flow rate.

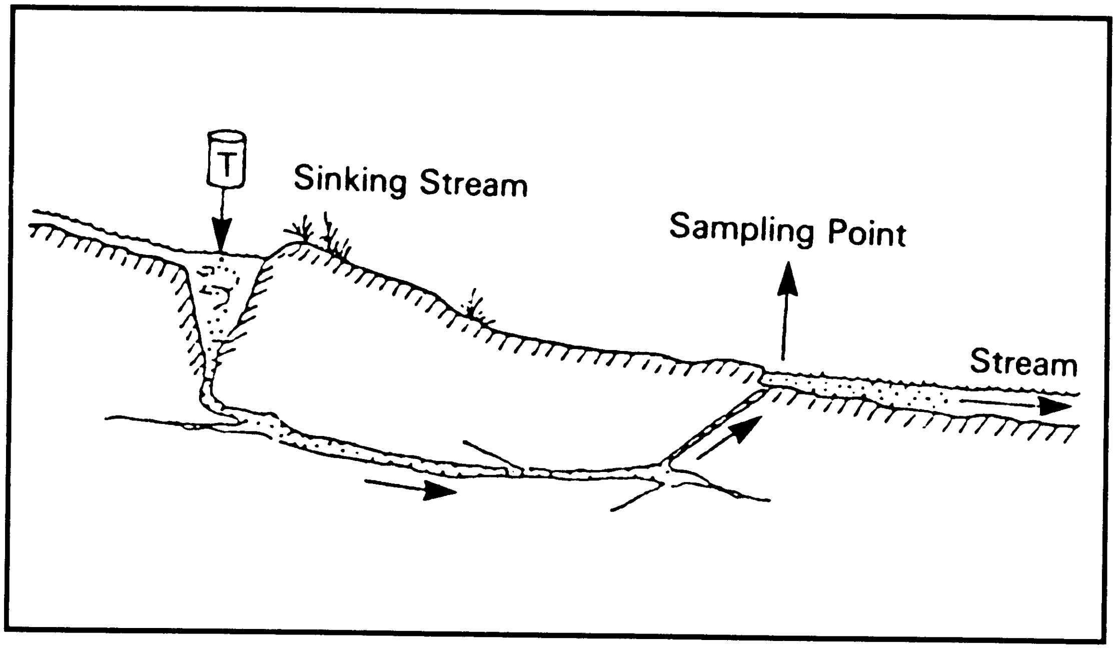
Ecological data can be collected using field methods that measure populations and other ecologic variables. These data can then be used to measure ecologic health. For example, the Ohio EPA has developed an index, the Qualitative Habitat Evaluation Index, that reports a stream's water quality as estimated by a survey of relevant habitat parameters (U.S. Department of Agriculture, 1992). In general, an ecological assessment of surface water quality is performed either by measuring the population of specific indicator organisms or assessing the health of the ecosystem as a whole by measuring the diversity and relative abundance of the species present. The similar use of ground water fauna to assess ground water quality has also been suggested in the literature, although not utilized extensively (Ward and Stanford, 1989; Ward, Voelz, and Harvey, 1989). As methods for assessing the importance of ground water ecosystems become available, they can be incorporated into the overall resource assessment.

Indicator studies that measure ground water and surface water interchange include isotopic studies and tracer investigations. These techniques can provide information on flow velocity and direction and can be adapted to cover sizeable streams and lakes Isotopic methods rely on the comparison of the concentrations of such naturally-occurring isotopes as oxygen or hydrogen in the ground water and in the stream to estimate the share of streamflow derived from ground water.

Tracer studies, such as those described by Bencala (1984) or Castro and Hornberger (1991) may yield approximations of the "mixing" of stream water with the adjacent and underlying ground water in alluvium. An example of the use of ground water tracers is shown in Figure 9 (USEPA, 1987). In this Figure, the tracer (T) is placed into the surface water at the sinking stream. The tracer will flow with the ground water and may be detected at downgradient sampling locations. Once the tracer is identified through sampling, ground water scientists can determine the direction and velocity of the ground water flow and any interaction between surface and ground water. Depending on the relationship of the interaction between the ground water and surface water bodies, tracers may also be used to estimate time of travel from specific points in the aquifer to the discharge point in a stream, or from the stream to a specific point in the aquifer. Tracers may include anions such as chloride and bromide; cations such as strontium, potassium, sodium, and lithium; dyes such as fluorescein and rhodamine WT; and naturally occurring substances.

Ground water and surface water interaction can also be assessed on a wider scale, often indirectly. For example, during the dry season, ground water discharge (i.e., base flow) may account for the entire flow of a stream. When streamflow has contributions from both surface water runoff and base flow, the portion that is base flow can be estimated using a variety of techniques. One such technique is hydrograph separation, which is the analysis of streamflow over time to estimate the relative contributions of surface runoff, ground water discharge, and shallow lateral subsurface flow above the water table (i.e., interflow). Soil interflow can account for a large percentage of runoff in watersheds having thin, permeable soils overlying low-permeability, fractured bedrock (Fetter, 1988). Hydrograph separation may be applied to a range of watersheds, from those of small streams to major river basins (USEPA, 1990).

Figure 9
Use of Ground Water Tracer to Check Source of Water at Discharge Point in Streambed



Source: USEPA, 1987

Regression analysis and numerical flow models use watershed data to estimate ground water and surface water interaction, usually on a watershed-wide scale. Regression analysis correlates the base flow with stream-basin characteristics, such as the drainage area of the watershed or the flow duration ratio. The flow duration ratio is a comparison of the frequency of the low flow rate of the stream with the frequency of its higher flow rate. Numerical flow models generally divide flow systems into a finite set of geographic cells with differing hydrologic properties. The models can generate an estimate of ground water discharge for each cell. Seepage studies can also be used to determine the quantity and quality of ground water discharging to a surface water body at multiple points. In a seepage study, measurements of streamflow are used to construct water balances for reaches between measurement sites. Calculation of ground water discharge is used to identify gaining or losing reaches.

Presentation of Data/Information

Data and information produced by the methods mentioned above can be presented in various forms. Maps can illustrate the locations of significant ground water and surface water interaction, and indicate flow direction. Tables or graphs may be more appropriate for presenting quantitative information and for illustrating temporal changes. For example, water quality information for specific sample points may be presented in tables. These forms of presenting data may also be used together. A map might show collection points and trends in the quality of ground and surface water in a region, while a table might display the relative abundance of various biological species in a specific water body. If substantial amounts of georeferenced data area available, a Geographic Information System (GIS) may be useful to assemble, store, and manage the information and assist ground water scientists in the development of maps.

Considerations

Managers need to consider the fact that all methods of assessing ground water and surface water interaction have limitations. Also, not all methods are universally applicable. For example, direct measurement of ground water flow using seepage meters may provide acceptable data for a specific point over a period of time, but may introduce large errors when extrapolated over extended time frames or a large area. Hydrograph separation and numerical methods may be effective for larger areas, but these methods generally provide little information on local areas of ground water and surface water interaction.

The applicability of individual methods is also dependent on the hydrogeologic setting. The application of some methods may be inappropriate in areas: with karst geology and variable base flow, with peaking after rainfall or snowmelt events, or with numerous seeps. For example, applying typical hydrograph separation techniques in these areas may provide gross underestimates of the ground water discharge component of the hydrograph.

In applying all of the methods discussed above, careful attention should be given to determining the temporal fluctuations. Data covering only a snapshot in time will not accurately depict temporal variations in ground water and surface water interaction. At different times throughout the year, the direction, quantity, and quality of flow between ground water and surface water may differ. Also, the intermittent pumping of nearby wells can have a pronounced effect on local water levels. Unless the effects of well pumpage on the potentiometric surface are specifically desired, personnel responsible for collection of water-level data should avoid collection of data from or near a well that is pumping or has recently been pumped. Pumping artificially lowers the potentiometric surface, which may take some period of time to return to equilibrium. Tides may also affect water levels in wells. Managers should consider this effect when interpreting water-level data in tidal areas.

The methods described above may require investment in equipment ranging from 55-gallon drums (used as seepage meters) to sophisticated electrical probes (for geophysical investigations) and expensive mainframe or minicomputers (for numerical flow models). Isotope or tracer studies covering large areas can similarly require a significant commitment of resources. The presence of naturally-occurring chemicals that can be used as tracers, however, can help reduce this resource demand. More generalized methods may be appropriate for larger areas. Application of numerical flow models may be extremely resource-intensive, but may provide the most reliable results for large study areas. Clearly, the resource commitment will vary depending on the method selected and the scope of the study.

One final consideration is that the interaction of ground water and surface water and the significance of this interaction in terms of water quality and ecological effects is an emerging field of study. Therefore, existing information may be limited, and some older information may be based on outdated methods and have limited usefulness. Thus, any assessment of ground water and surface water interchange should examine the implications of new developments in this area.

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Component #8: Ground Water Budget

Definition

A ground water budget is a quantification of all the natural and anthropogenic gains of water to, and losses of water from, the ground water reservoir.

Objective

A ground water budget can be used to make a qualitative and/or quantitative assessment: of ground water flow into or out of the ground water reservoir, of ground water storage in the reservoir, and of the response of water levels to varying amounts of recharge and discharge. Ground water budgets assist managers in assessing the current extent of ground water recharge and in forecasting possible supply inadequacies resulting from increased ground water use.

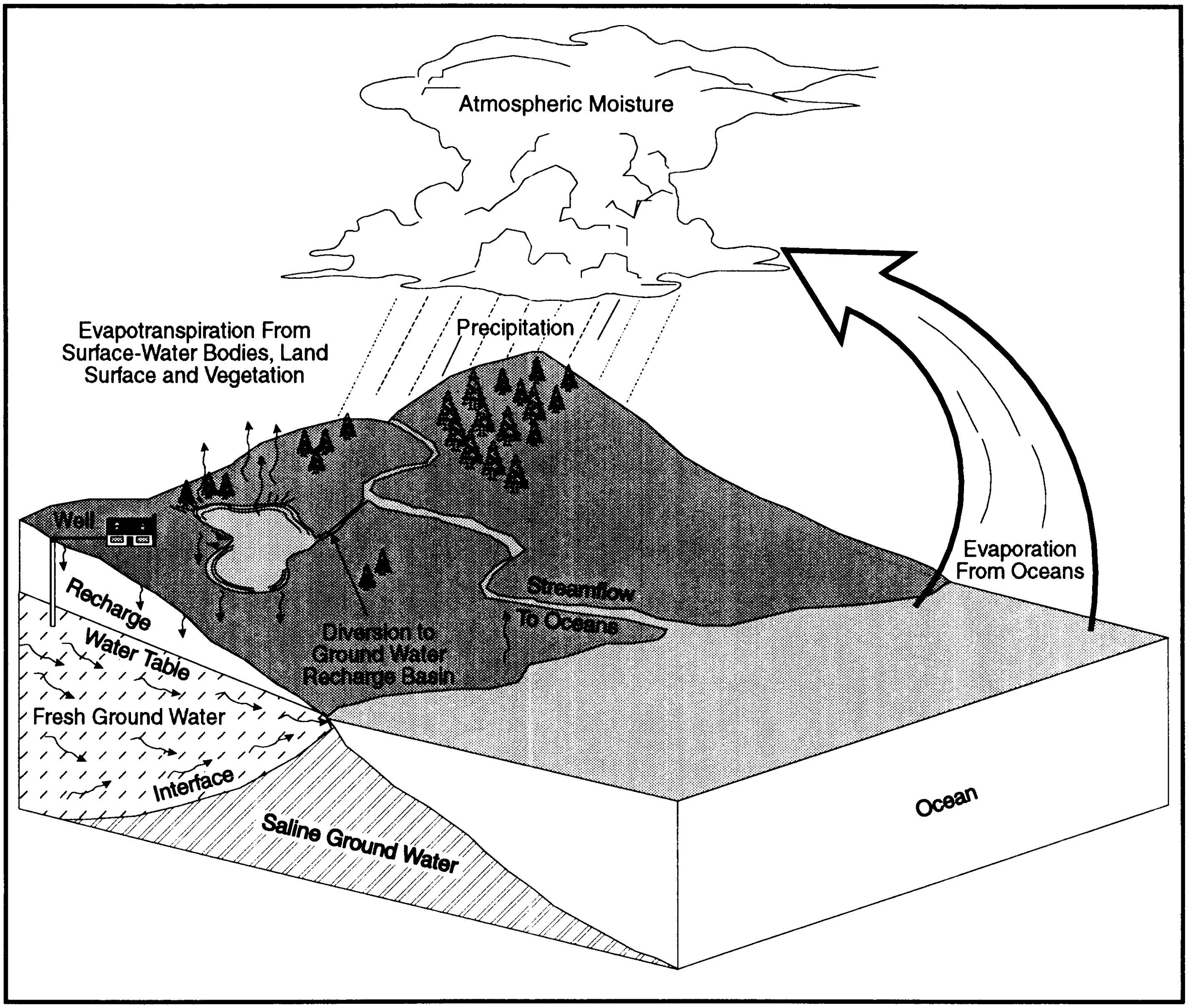
Data Needs

The information needed to develop a ground water budget should include all the available data regarding the amounts of water traveling through the different parts of the hydrologic cycle. Components of the hydrologic cycle that should be included in developing a ground water budget are shown in Figure 10 (Walker, 1993). The following data are essential in preparing a ground water budget:

- hydrologic data
- quantity of evapotranspiration
- aquifer and overlying and underlying material characteristics
- anthropogenic additions to and withdrawals from the ground water reservoir

Hydrologic data, including precipitation and streamflow information, are needed to estimate the amount of water reaching the ground surface and, potentially, ground water.

Figure 10
Water Budget



Source: After Waller, 1993

Precipitation infiltrating through the soil and reaching the zone of saturation becomes part of the ground water flow system.

A number of factors determines the rate of runoff and infiltration of precipitation, including permeability of soils, rate of precipitation, vegetative cover, time of year, and the slope of the receiving area. Urban and other developed surfaces, soils with low permeability, and unvegetated open tracts of land tend to produce less infiltration and more runoff than naturally vegetated, undisturbed areas. Runoff also occurs once soils reach field capacity and can no longer accept water into storage. The rate, intensity, and duration of precipitation are also important factors in determining the amount of runoff. Storms producing moderate amounts of rainfall over extended periods of time generally supply significantly more recharge than short duration, intense storms, because precipitation from heavy storms is introduced more rapidly than it can infiltrate the ground surface. Finally, land slope (i.e., topography) influences the amount of water entering the soil or surface water; for the same surficial-sediment type, steep slopes or mountainous regions produce more runoff than areas of lower relief. Refer to Component #6 for further discussion characterizing ground water recharge and discharge.

Evapotranspiration is the total amount of water traveling from the land to the atmosphere by (1) evaporation of open waters, (2) evaporation from soil surfaces and shallow water tables, and (3) transpiration of water from the soil by plants (Freeze and Cherry, 1979). Evapotranspiration is affected by the local climate, amount and types of vegetation, and the local soil characteristics. With respect to the water budget, evapotranspired water is unavailable to ground water reservoirs. Measurement of evapotranspiration is extremely complex and estimates for a given region will vary widely.

Aquifer and overlying and underlying material characteristics influence the rate of ground water recharge and discharge. An aquifer may be in equilibrium, meaning that the amount of recharge equals the amount of discharge, with the potentiometric surface for confined aquifers and the water table for unconfined aquifers remaining constant over time. Most often, however, recharge and discharge are unequal and the water-table surface/potentiometric surface fluctuates over time. This fluctuation, as measured by changes in water levels in wells, can be used to estimate changes in the volume of water stored in the aquifer, a factor that must be accounted for in the water budget.

Anthropogenic additions and withdrawals of ground and/or surface water (i.e., imported and exported water) should be taken into account when preparing a ground water budget. Localized surface water extractions may have a negative impact on the ground water system if the surface water feature is a source of ground water recharge. Extraction of water by wells reduces the amount of available ground water. Conversely, water may be added to the ground water system by sewage discharges, return flow from irrigation, and recharge via wells to control subsidence or salt water intrusion.

Methods

Once estimates for all factors have been obtained, a ground water budget can be calculated through the use of a simple arithmetic equation. The equation may be solved for any of its variables if the other quantities are known. Results of the equation should be used with caution, however, because errors can occur in estimating some of the variables. The equation is as follows:

Net ground water recharge (change in ground water in storage) =

(infiltrated precipitation + surface water inflow +
imported water + ground water inflow)

\- (evapotranspiration + surface water outflow +
exported water + ground water outflow)

For the purpose of the ground water budget, each of these terms is defined as follows:

- **Infiltrated precipitation** is the quantity of precipitation that reaches the saturated zone

- **Surface water inflow** is the quantity of surface water that recharges the ground water reservoir via ground water/surface water interaction

- **Imported water** is the quantity of water that is recharged to the aquifer artificially (i.e., by man) for such purposes as storage, disposal, or replenishment of ground water resources

- **Ground water inflow** is the quantity of ground water that enters the ground water reservoir from areas upgradient of the region of consideration

- **Evapotranspiration** is the combined quantity of water entering the atmosphere through evaporation from soil surfaces and shallow water tables, transpiration from the soil by plants, and evaporation from open bodies of surface water hydraulically connected to the ground water reservoir

- **Surface water outflow** is the quantity of ground water discharged to wetlands lakes, streams, drainage ditches, and/or rivers that are hydraulically connected to the ground water reservoir

- **Exported water** is ground water that is removed from the aquifer by man via wells

- **Ground water outflow** is the quantity of ground water that exits the ground water reservoir to areas downgradient from the region of consideration

Various methods can be used to obtain the data necessary to complete a ground water budget. These methods, including literature searches and field/laboratory techniques discussed under other Components, can be used to collect the following data:

- precipitation data
- aquifer characteristics
- stream discharges
- anthropogenic additions and withdrawals
- soil maps and profiles
- evapotranspiration

Precipitation data, stream discharges, and soil information can be readily obtained by contacting Federal, State and local agencies. The National Oceanic and Atmospheric Administration (NOAA) maintains rainfall records for reporting stations throughout the United States, as well as pan evaporation data for selected stations. The U.S. Geological Survey (USGS), and State and local agencies often maintain stream discharge data. Soil maps and a soils data base are maintained by the Soil Conservation Service (SCS) for many localities and are updated by county soil scientists familiar with local conditions.

Evapotranspiration can be measured in a traditional (non-suction) lysimeter. This device is a field apparatus containing soil and vegetation that is used to approximate evapotranspiration under actual field conditions. Pan-evaporation rates in the field can also be used to estimate evaporation. Alternatively, evapotranspiration can be estimated using empirical methods that assume an upper limit to the amount of evapotranspiration possible, and assign a quantity to potential loss of water by evapotranspiration that relies on climatic variables (Fetter, 1988). One of these methods, devised by Thornthwaite, uses air temperature as an index of the amount of energy available for evapotranspiration (Dunne and Leopold, 1978). Potential evapotranspiration is expressed as a function of mean monthly air temperature and average monthly sunlight, expressed as a function of month and latitude. This method is fairly accurate for estimated annual potential evapotranspiration, particularly in humid areas; however, because it does not account for types or rates of growth of vegetation, the method is inadequate for estimating potential evapotranspiration in the spring and early summer growing seasons (Fetter, 1988).

Aquifer characteristics effect the amount of ground water that can be held in storage in the ground water reservoir. Aquifer characteristics may be determined from existing data from subsurface investigations, or if no data exist, from aquifer tests, well logs, and samples of geologic materials.

Records of anthropogenic influences on ground water systems are often scarce in some regions of the United States. Records of the number of pumping wells within the ground water reservoir can often be found in local health department files, State geologic surveys, State agency well registration programs, or water regulatory or research agencies. Records of industrial discharge into surface and ground water may be scarce and/or inaccurate. Anthropogenic additions or withdrawals may be negligible in comparison to the amount of natural ground water recharge and discharge in humid areas. However, particularly in arid and semi-arid climates, these additions or withdrawals may be significant.

Presentation of Data/Information

Identifying local and regional recharge and discharge areas, which are important in determining a ground water budget, should be a goal of the presentation of data. This presentation would be similar to those for the recharge and discharge characterization found in Component #6. Topographic, geologic, and soils information are usually displayed on two-dimensional maps. These data are helpful in locating recharge and discharge areas. Hydrologic information, aquifer characteristics and related data can be compiled into tables and charts. Geographical Information Systems (GIS) may be helpful to ground water scientists in assembling, storing, and managing georeferenced information and in producing initial estimates of the positions of map contours and hydrologic boundaries. For each parameter in the ground water budget equation, values obtained for different ground water study areas can be presented in tabular, graphical or matrix form for ease of comparison.

Considerations

Quantification of the parameters in a ground water budget may rely primarily on existing data. Special care should be exercised, however, in correlating the ground water budget of one area to that of another or to a large region because hydrologic, geologic, and anthropogenic parameters can vary over small distances.

Managers will find calculations of the amounts of ground water recharge and discharge important in planning for the future use of ground water resources. Expected and future withdrawals from an aquifer can be compared to the existing recharge to determine the availability of, and impact on sustainable ground water supplies.

Managers should be aware that pumping water from an aquifer will lower the aquifer's potentiometric surface or water table even if the amount of water withdrawn is less than the natural recharge. This occurs because the natural (i.e., predevelopment) potentiometric surface or water table of an aquifer depends on the equilibrium conditions of natural recharge and discharge. Removing water stored in an aquifer lowers aquifer water-levels and reduces the natural flow of ground water to those surface water bodies that are in connection with the aquifer. Withdrawal of ground water may induce additional recharge from surface sources, lowering lake levels and reducing wetlands and stream flows. Ground water withdrawals from one aquifer can induce leakage from adjoining stratigraphic layers.

Error in the result of the water-budget equation is the result of all the errors incorporated into the individual components. Several of the components are particularly difficult to accurately estimate. Calibration of a computer model of ground water flow produces a balance between ground water recharge and discharge, plus or minus changes in storage. Oftentimes, recharge is estimated as part of the calibration process.

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Component #9: Chemical and Physical Characteristics of Aquifers and Overlying and Underlying Materials

Definition

Chemical characteristics of an aquifer and its overlying and underlying units are distinguishing attributes that describe the chemical composition of these geologic materials. Physical characteristics refer to the texture and structure of these geologic materials.

Objective

The objective of this element is to provide basic information on the chemical and physical properties of the geologic materials that are in contact with ground water, in order to better understand their impact on water quality and the fate and transport of contaminants.

Data Needs

To assess these characteristics, data relating to each of the following three zones should be collected:

(1) soil material (weathered surface layer that supports plant growth)
(2) unsaturated geologic materials underlying the soil
(3) saturated geologic materials (confining units and aquifers)

These data should include the following:

- overall mineralogy of the material
- overall chemistry of materials
- content and distribution of organic matter, plant material, and bacteria
- physical characteristics (texture and structure) of materials

- depositional nature of sedimentary materials and degree of fracturing
- climatic variables
- moisture content
- hydraulic characteristics of the material in each layer
- advection and hydrodynamic dispersion characteristics
- degradation characteristics
- cation and anion exchange capacity

Information about the overall **mineralogy** of the geologic material comprising a zone can provide a better understanding of the zone's chemical and physical characteristics (Freeze and Cherry, 1979). For example, minerals may be relatively soluble, leading to the formation of conduits or karst conditions that result in rapid transport of contaminants into or through the aquifer. Mineralogy also affects the type and amount of small chemical charges present on the surface of geologic particles. These charges determine the cation and anion exchange capacity of the material, i.e., the capacity of the material to retain charged particles such as contaminants (Fetter, 1988). Pore water chemistry of subsurface geologic units is greatly affected by the mineralogy of the geologic materials (Pucci, et al, 1992). Swelling clays, which expand when wetted and are of low permeability, exhibit highly variable infiltration capacities. During drying, they contract and may develop dessication cracks. Precipitation following dry periods readily infiltrates the cracks before they swell, and provides rapid potential recharge and a transport mechanism for contaminants. Although the rate of dissolution of silica is extremely small, in bedrock aquifers composed of igneous and/or metamorphic rocks, the width of fractures can increase as recharge water dissolves silica from fracture walls (Freeze and Cherry, 1979). Chemical characteristics of materials of an aquifer and its overlying and underlying formations also affect the interactions, conversions, and degradation of constituents migrating toward or through the aquifer.

Naturally-occurring, non-living **organic matter** is relatively insoluble and tends to accumulate near the surface of the soil. This organic matter, generally in the form of humus (i.e., partially decomposed plant and animal material), may have very high cation and anion exchange capacities and tends to capture some portion of potential contaminants before they enter the ground water (Fetter, 1988). Organic matter may also be found in underlying paleosols (i.e., buried soils). A total organic carbon analysis can determine the amount of organic matter in a representative sample of soil. Living material may affect aquifer susceptibility to contamination by temporarily immobilizing contaminants through biological uptake. Plants growing on the soil layer can also affect susceptibility by modifying the hydrologic balance. Soil water uptake by plants decreases the amount of water recharging the aquifer, thereby decreasing the potential contaminant transport mechanism to the aquifer. Absence of vegetation is conducive to runoff, regardless of the soil permeability (Hanks and Ashcroft, 1980).

Information on the **physical characteristics (texture and structure) of materials** is important for determining their hydraulic properties (Taylor and Ashcroft, 1972). As discussed in Component #4, texture and structure determine the porosity of unconsolidated media. Texture is a measure of the size distribution of particles that compose sedimentary geologic material. Geologic material comprised of well-sorted (fairly equal-sized) particles generally is more porous than poorly sorted material. Structure is defined by the arrangement of particles within the material. The arrangement (packing) of particles controls the ability of fluids to travel through the material. Loose packing can correspond with little resistance to flow (even with small particle size) and tight packing can indicate a restriction of flow (Hanks and Ashcroft, 1980). Preferred pathways, such as macropores that develop when large plant roots are removed or when desiccation cracks form can develop in surficial materials and "short circuit" the flow of water through these materials.

The **degree of fracturing in igneous, metamorphic and sedimentary rocks** can indicate the potential for fluid to flow through these materials. Porosities of unfractured igneous and metamorphic rocks are generally very low; however, fractures that have developed in these rocks and in consolidated sedimentary rocks, because of structural activity (e.g., folding and faulting), can, if interconnected, dramatically increase hydraulic conductivity and increase the flow of ground water and migration of contaminants. Fractures can be widened through the dissolution of silica in the rock matrix by recharging ground water, thereby further increasing permeabilities. The depositional nature of volcanic rocks can provide information on their physical characteristics of a zone. For example, lava often covers gravels deposited by streams flowing over previously deposited lavas, thus creating rock masses with gravel interbeds that can have high bulk permeability (Freeze and Cherry, 1979).

The **depositional nature of sedimentary materials** can provide insight into the physical characteristics of the materials. For example, rivers and streams tend to deposit their coarsest materials near streambanks and increasing amounts of finer materials at increasing distances from the stream. Stream-deposited materials also are often seasonally layered as the result of flooding and erosive storm events. Sedimentary materials formed by lake deposition tend to be fine and tightly-packed, while airborne sedimentary materials tend to be fine and loosely-packed (Ritter, 1986).

The fate and transport of contaminants in the subsurface is also related to the area's **climatic variables**. In particular, precipitation and subsequent infiltration have an important effect on the movement of contaminants through the subsurface. See Component #8 for a discussion of the ground water budget and the importance of climate.

Moisture content is an indication of the water-storage capability of the soil layer. Moisture content is related to the physical characteristics of the soil, the hydraulic pressure head in the soil and whether the soil is drying or being wetted (Freeze and Cherry, 1979).

The **hydraulic characteristics** of a geologic material are a measure of the material's capacity to hold and transmit water. A discussion of hydraulic characteristics can be found in Component #4.

Two physical processes that determine contaminant migration through porous geologic media are **advection and hydrodynamic dispersion** (Freeze and Cherry, 1979). Advection is the transport of contaminants by flowing ground water. Hydrodynamic dispersion is the spreading of dissolved contaminants due to both molecular diffusion and mixing caused by ground water flow. As a contaminant is dispersed through the ground water, the concentration of the contaminant may decrease (through dilution) below detection limits. Decreases in contaminant concentrations due to dilution do not indicate a decrease in the total mass of contaminants.

Organic contaminants are subject to the process of **degradation** that may change the chemical constituents of contaminants into other hazardous or non-hazardous constituents. The primary form for degradation is microbial action in aerated porous media. As conditions for microbial action in an aerobic environment are more likely to exist near the soil surface, degradation will occur primarily in the soil layer. Organic contaminants vary greatly in the rate at which they microbially degrade. The rate at which an organic contaminant degrades depends on the concentration of the contaminant and the chemical properties of constituents within the contaminant. Organic-contaminant degradation rates tend to decrease exponentially with decreasing contaminant concentration. Degradation rates for organic chemical constituents are expressed in terms of the number of days required to degrade one-half of the constituent mass (i.e., half-life).

As previously discussed, the **cation and anion exchange capacity** of organic matter and geologic media tend to retard the migration of contaminants. The combined effect of these advection-resisting forces is a contaminant concentration that decreases with distance (i.e., attenuation) from the point of contamination (Fetter, 1988).

Methods

To meet the objective of this Component, the methods discussed herein include not only methods to compile information on chemical and physical characteristics of geologic materials, but also methods to use this information to predict the extent and concentration of contaminants within aquifers and their overlying and underlying materials. Data on the chemical and physical characteristics of geologic materials can be collected through a literature search of existing data and by using a combination of field and laboratory methods. The collected chemical and physical characteristics data can then be used in chemical fate and transport models to predict the extent and concentration of contaminants.

A literature search for existing data may significantly reduce the resources required to adequately define the chemical and physical characteristics of the aquifer and its overlying/underlying materials. A large amount of data on the study area may exist in published and unpublished reports (see Components #1, #2 and #4). The U.S. Environmental Protection Agency (EPA) offices, such as those that oversee the Resource Conservation and Recovery Act, Superfund, Underground Storage Tank, and Underground Injection Control regulatory programs, require hydrogeologic data from facility owners and operators including information about chemical and physical characteristics of aquifers and their overlying materials. Sources of data obtained through a literature search may include well logs, geologic information (including maps and cross-sections), soil surveys, ground water reports, and computerized data bases.

Data on the chemical and physical characteristics of geologic media can be obtained from such publications, institutions, and agencies as:

- U.S. Geological Survey (USGS) and State geological surveys (geologic and hydrogeologic maps and reports)

- U.S. Department of Agriculture's Soil Conservation Service (SCS) (soil surveys and data bases)

- State land grant and other universities and their extension services, geology departments, and soil science departments

- EPA Environmental Research Laboratories in Ada, Oklahoma and Athens, Georgia.

It is important to note that the fate and transport of contaminants are greatly affected by interactions between the contaminant and geologic materials. To fully understand fate and transport, therefore, it is also necessary to know the specific chemical and physical characteristics of the contaminant(s). Once contaminants of interest have been identified, information on their characteristics can be obtained through various chemical data bases. For a listing of such data bases see Table 3.

Due to the number of potential contaminants and the potentially complex interactions between these contaminants and geologic materials, a discussion of the chemical and physical characteristics of specific contaminants is beyond the scope of this document. However, further information can be obtained from the U.S. Department of Energy's Multimedia Environmental Pollutant Assessment System (MEPAS) (Pacific Northwest Laboratory, 1987) or from the American Chemical Society's Handbook of Chemical Property Estimation Methods (Lyman et al., 1990). Soil-water partition coefficients for organic pollutants are found in Fetter (1988). The Data Collection Handbook Supporting Modeling the Impacts of Radionuclide Material in Soil (Argonne National Laboratory, 1993), prepared for

Table 3
Chemical Data Bases Containing Properties of Common Ground Water Contaminants

Data Base	Description	Vendor	Address
CHEMEST	Properties of organic compounds, including water solubility, soil adsorption coefficient, vapor pressure, water volatilization rate, liquid viscosity, and Henry's Law Constant	Technical Database Services, Inc.	10 Columbus Circle New York, NY 10019
DATALOG	Properties of 12,000 organic compounds and metals, including water solubility, octanol/water partition coefficient, vapor pressure, ultraviolet spectra, dissociation constant, soil adsorption coefficient, evaporation rate, Henry's Law Constant, biodegradation, and photoxidation	Technical Database Services, Inc.	10 Columbus Circle New York, NY 10019
CHEMFATE	Properties of 1,730 chemicals including chemodynamic properties (e.g., log octanol/water partition coefficient, log acid dissociation constant, soil adsorption coefficient), transport properties (e.g., bioconcentration, evaporation from water, Henry's Law Constant, soil column transport), degradation data (e.g., microbial degradation, oxidation, and photolysis), and water and soil monitoring data	Technical Database Services, Inc.	10 Columbus Circle New York, NY 10019
QSAR	Properties of 56,000 chemicals, including water solubility, pKa (expression of strength of organic acids and bases), log octanol/water partition coefficient, and 11 structure-activity-relationship (SAR) models that can be used to calculate physical-chemical properties	Technical Database Services, Inc.	10 Columbus Circle New York, NY 10019
ENVIROFATE	Transport and degradation properties of more than 800 chemicals, including biodegradation, oxidation, hydrolysis, water solubility, and vapor pressure	Chemical Information Systems, Inc.*	7215 York Rd. Baltimore, MD 21212

* Maintained by Chemical Information Systems, Inc. for U.S. EPA's Office of Pollution Prevention and Toxics

the U.S. Department of Energy, provides useful information on chemical and hydrogeological parameters.

Data that cannot be obtained from existing sources may be obtained from field sampling and testing. The mineralogy, chemical makeup, content and distribution of organic matter, bacteria and plant material, moisture content, and hydraulic characteristics of geologic materials can often be determined in the laboratory from field samples. The physical characteristics of sedimentary, igneous, and metamorphic rocks are often determined directly from field observations. To avoid additional field investigations, samples should be collected whenever possible from on-going operations that require drilling or collection of geologic material. Samples can be taken from cores made during the construction of wells or from cores taken for general construction or excavation purposes. In addition, surface and subsurface geophysical methods such as seismic refraction, electrical resistivity/conductivity, and borehole geophysics can be used to determine the physical characteristics of geologic materials.

Chemical and physical characteristics of aquifers and their overlying and underlying materials can often be determined in the field. As mentioned in Component #4, field measurement of hydraulic conductivity is representative of the geologic materials throughout the area of influence of the aquifer test well; laboratory determinations are only valid for the site of the sample. Methods and considerations for using field tests such as aquifer and tracer tests are discussed in more detail in Component #4.

Geographic location (e.g., township, range, section, or, preferably, latitude and longitude) should be assigned to data collection sites. If precise locations are available using latitude and longitude, data can be input to a Geographic Information System (GIS) that can be used to combine the data, interpolate values between sampling points, and provide rough, initial estimates of chemical and physical characteristics across a study area.

Presentation of Data/Information

Information on the chemical and physical characteristics of aquifers and their overlying/underlying materials may be most easily understood and interpreted when presented in map, chart, or graphical format. Maps are useful to show the geographic distribution of hydraulic properties over a region. Separate maps can also be prepared for different aquifers or zones. If the area to be mapped contains significant variations in chemical and physical characteristics, mapping may require a large amount of data to adequately delineate where these changes occur.

Vertical column and cross-sectional profiles can also be prepared to show the depth and thickness of each aquifer or zone and its associated chemical and physical characteristics.

Data on aquifer (and overlying and underlying material) characteristics can be correlated to geographic locations and then put into a GIS for preparation of graphical displays or preliminary drafts of maps.

It is important to preserve the original data in tables or data bases. These tables or data bases may be needed for subsequent manipulation of the data or modeling of the hydrogeologic setting. Even when data are presented using a graphical format, the raw or complete numerical data set should also be made available.

Considerations

The scale at which one assesses chemical and physical characteristics of aquifers and their overlying and underlying materials depends on the specific application. More data will be needed where geologic conditions change significantly within short distances. Adequate characterization of chemical and physical characteristics of materials in these settings generally requires a vast amount of data. Collection of large amounts of data may be very costly, especially if new test wells are to be installed. For this reason, it is especially important to conduct a literature search to determine and locate existing hydrogeologic data.

When using existing data, it is important to consider their accuracy and reliability. Often this can be accomplished by examining the methods that were used to collect the data. The age of the data should also be considered, because detection methods and detection limits have improved over time.

Choosing sites for data collection activities must be done carefully to maximize the applicability of the new data. New data collection sites should be selected only after considering all available hydrogeologic data including terrain- and boundary-forming features such as faults, low permeability formations, and recharge and discharge areas. Well depths must also be considered when planning aquifer tests that require pumping.

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Component #10: Ambient Ground Water Quality

Definition

Ambient ground water quality is the quality of ground water at a baseline time selected by the decision-making agency. Ambient quality may be the natural quality of ground water or may be the natural quality as impacted by widespread historical contamination. Ground water quality is assessed by means of extensive tests that measure physical, chemical, biological, and radiological constituents of representative samples.

Objective

Ambient ground water quality is the existing condition on which future resource management should be based. Ground water quality data can play a key role in developing resource protection policies and should be collected to assess local ground water quality conditions in shallow as well as deeper, confined aquifers. The data may provide an assessment of the status of available drinking water supplies or may serve as a baseline for future comparisons of ground water quality. Ground water quality data are often used by resource managers to encourage compliance with existing protection policies, as in the case of drinking water standards, and in the development of new standards. Ground water quality data also improve the understanding of the ground water flow system. A fundamental knowledge of ground water quality should be considered an integral part of any ground water resource assessment.

Data Needs

To assess the ambient ground water quality of an aquifer, managers should collect data and information on:

- sampling location (areal extent and depth)
- climatic and infiltration characteristics

- mineralogy of geologic and soil materials
- chemical parameters (i.e., constituents and their concentrations)
- organic parameters
- radiological parameters
- biological parameters (i.e., species and their concentrations)

Sampling location and sample depth are essential data when collecting ground water quality samples. The depth from which samples are drawn is needed because it is usually important to know the aquifer from which the sample is obtained. The dates samples are taken are important for determining trends in ground water quality, especially for shallow aquifers that respond to seasonal variations.

Climatic and infiltration characteristics can affect ground water quality. Chemical quality of ground water supplies can be directly related to precipitation and infiltration. Shallow aquifers are influenced more directly by precipitation than are deeper, confined aquifers. Confined aquifers receive recharge water from leaky confining layers, through fractures that enhance interaction between aquifers, or from direct recharge where the aquifer outcrops or is close to the land surface. Refer to Components #6 and #8 for a more detailed discussion of climatic variation and recharge and discharge.

The quality of ground water is also affected by the **mineralogy of geologic and soil materials**. The mineral composition of aquifers, aquitards, and overlying unsaturated material has a substantial influence on the quality of ground water. Ground water quality within a particular region may vary greatly as a result of spatial differences in the abundance of the different minerals comprising the geologic materials. The geochemical interrelationships between water and rock are complex and beyond the scope of this Component; however, additional information can be found in Component #9. The hydrogeologic setting of the aquifer may also impact water quality. For example, salt water intruding into aquifers in coastal areas may severely impact water quality. Also, shallow aquifers, which are hydrologically connected to surface water bodies, may reflect surface water quality.

Drinking water standards established by the Safe Drinking Water Act (SDWA) serve both as a basis for appraisal of the results of chemical, radiological, and biological analyses of water and to establish the suitability of the water for drinking water. **Chemical parameters** listed in the drinking water standards include both inorganic and organic parameters. The listed parameters, both naturally occurring constituents and contaminants introduced by man are found in ground water supplies of drinking water. Primary and recommended limits for inorganic constituents in drinking water have existed for many years. The major inorganic constituents that are used in assessing ground water quality and for which the U.S. Environmental Protection Agency (EPA) has set recommended limits are nitrate, sulfate, and chloride. These and other inorganics should be monitored to detect the presence of excessive levels of potential contaminants. Each parameter is unique and may have standards based on aesthetic qualities (i.e., appearance and taste) as well as health effects. Total dissolved solids, an EPA secondary standard, may be of concern in some settings and may, therefore, have to be monitored.

Other inorganic parameters often measured in ground water samples include calcium and magnesium, which are used to characterize the hardness. A variety of metals such as iron and manganese could cause household nuisances with precipitates, stains, and bad taste. The most common increases in concentrations of inorganics observed through monitoring programs are in sodium chloride and nitrate levels, but changes in other inorganic and organic constituent levels may also exist. The EPA has established maximum permissible concentrations for such inorganic parameters as: nitrate-nitrite, arsenic, lead, mercury, silver and fluoride. These constituents are considered to have significant potential for harm to human health at concentrations higher than permissible levels.

EPA has set recommended limits for organic constituents in drinking water, such as pesticide residues. Small amounts of naturally occurring dissolved organic substances are normally found in ground water, and pose little concern to human health. However, synthetic organic compounds are of much greater concern, as sewage treatment plants have difficulty in removing many of these compounds from waste streams. In addition, these compounds are more resistant to biological degradation. Examples of synthetic organic compounds include aromatic hydrocarbons (e.g., benzene, styrene, and toluene), industrial solvents (e.g., trichloroethane and tetrachloroethane), and pesticides. Synthetic organic compounds can enter ground water from the downward migration of contaminants released from a variety of sources including chemical spills, agricultural application of pesticides, and sanitary landfills.

The drinking water standards also include **radiological** parameters. Measurements of Radium 226 and Radon 222 are conducted to establish natural levels of radioactivity present in geologic materials. Gross alpha and gross beta are measures of radioactivity from natural uranium deposits or from manmade sources such as radioactive wastes. Testing for gross alpha activity is an efficient way to determine the existing radioactivity in ground water and is a qualitative measure most useful for screening purposes.

Changes in the **biological quality** of ground water are detected through sampling and analysis of biological parameters. For ground water quality, sampling and analysis of biological parameters is usually limited to the measurement of total coliform bacteria. Total coliform is used as an indicator of the presence of disease-causing viruses, protozoans, fungi, worms, and other bacteria associated with human or animal wastes. Positive total coliform test results are not necessarily indicative of the presence of harmful biological organisms. However, if a sample tests positive for total coliform bacteria, fecal or E. coli bacteria tests should be conducted to determine if either of these more harmful bacteria are present.

Methods

The methods used for collecting and assessing data will be determined by the objectives of the ground water quality assessment. Before designing and establishing a ground water sampling and monitoring program, a thorough search of existing data should be conducted. Sources of data include soil maps and reports, geologic and water-quality maps, geologic cross-sections, well logs, and published reports. This information is available from State geological survey offices, U.S. Geological Survey (USGS), the U.S. Department of Agriculture's Soil Conservation Service (SCS), State and local universities, State water research, quality and appropriations agencies, and local and regional planning agencies. Existing data, including chemical analyses of selected parameters may be available through local government health departments and planning agencies. The ecological description of ground water is a newly emerging science; ecological data are difficult to obtain, but may be available from academic sources.

Following a search and analysis of existing data, and the identification of data gaps, managers will need to consider a ground water monitoring program to fill the gaps. The following are generic steps for planning such a program (after Fetter, 1988):

- define the purpose and objectives of the program

- define locations of, and procedures for sampling (e.g., how many samples are needed, are there existing sampling points, are new sampling locations needed)

- determine the chemical constituents to be evaluated

- determine if constituents to be analyzed necessitate special well casing materials and/or sampling requirements

- develop a quality assurance/quality control (QA/QC) program

Such planning is essential to ensure the utility of the data collected. The above procedures should be followed to ensure that ground water quality data collected from the same sample points can be compared over time.

To evaluate the existing water quality of an area, the most appropriate sources of data may be existing wells and springs; the aquifers from which the water quality samples are collected should be determined. The distribution of these existing wells and springs should be evaluated to identify gaps in coverage. Sampling should occur throughout the study area, including any recharge and discharge areas. The design of the sampling program should consider the effects of anthropogenic sources on localized ground water quality.

If an adequate distribution of reliable, existing, sampling points does not exist, dedicated monitoring wells may have to be installed. These monitoring wells should be placed at points that are strategically selected, based on estimates of flow direction and travel time, to better monitor ground water quality in susceptible or remote areas. For example, dedicated ground water monitoring wells are often installed in the vicinity of wastewater-treatment sites, waste-disposal sites, or agricultural areas to monitor changes in ground water quality.

There are two general approaches for sampling ambient ground water quality: (1) sampling existing sites where ground water is accessible, including public and private wells and natural springs; and (2) sampling dedicated ground water monitoring wells if they are needed to supply additional information. For some purposes, for example determining the water quality of a highly transmissive aquifer after a recharge event, synchronizing the timing of the two sampling approaches is necessary. The timing of sampling is critical for aquifers with rapid ground water flow and for shallow aquifers with rapid recharge after storm events or when discrete events such as pesticide application occur. Sampling frequency should be considered when long-term monitoring is needed.

Sampling procedures and subsequent analyses of water samples should be well documented and should follow accepted standard methods. Ground water should be extracted from the source, tested for field parameters (such as pH, temperature, and specific conductance), containerized, treated with preservatives if needed, and analyzed on-site or off-site for targeted parameters. On-site, real-time analysis is a developing technology. Targeted parameters are defined by the specific objectives of the study. It is important to note that samples collected to establish trends over time should be taken from the same location and depth to ensure the comparability of results.

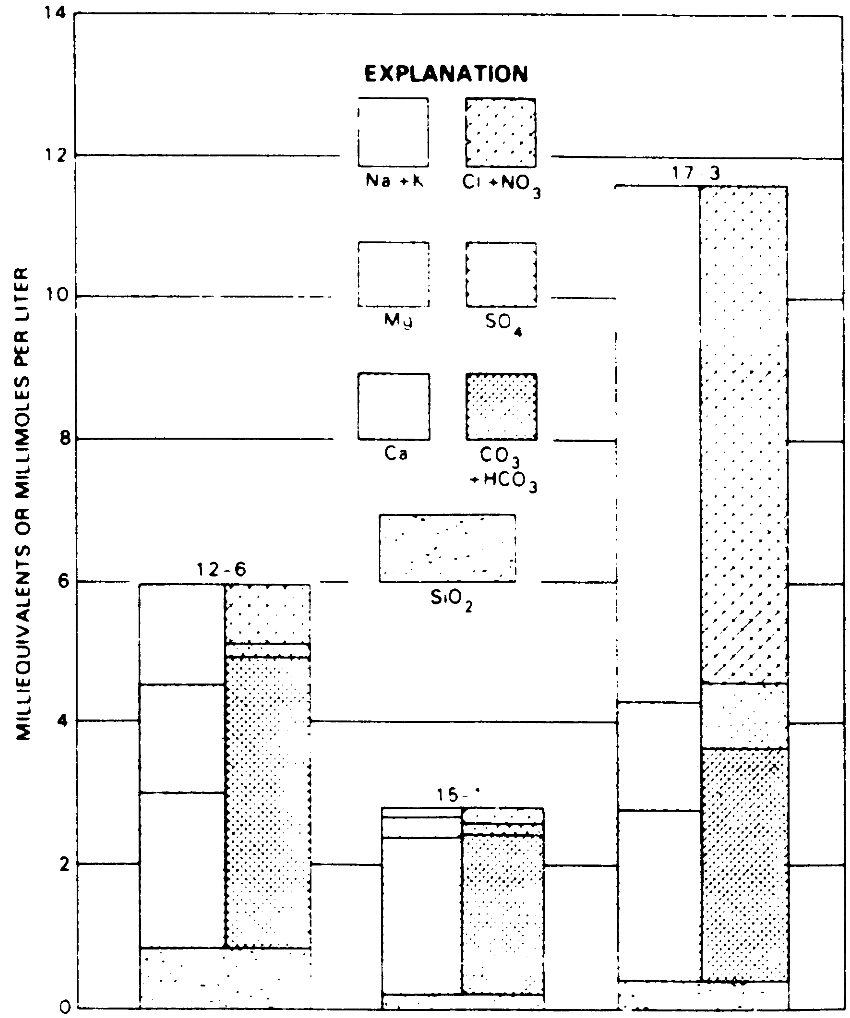
Presentation of Data/Information

Once ground water quality data are collected, the constituent parameters may be reported in a tabular format or on maps. The use of bar and line graphs, pie charts, and box charts may facilitate the interpretation of voluminous complex data, or data collected over time. Chemical characteristics of water quality can be presented graphically in geochemical diagrams such as bar, circle, Stiff, and trilinear diagrams (Driscoll, 1986). Examples of these diagrams are shown in Figures 11A through 11D (Hem, 1992).

A Geographic Information System (GIS) is a helpful tool to store, assemble, and manipulate different sets of georeferenced water-quality data for graphical presentation and statistical data analysis. Presentation of water quality data using a GIS can enhance the understanding of multiple parameters over a large area.

Interpretation of water quality data by ground water scientists, in conjunction with other hydrogeologic information, permits the development of water quality maps with lines of equal parameter concentration and boundaries of water quality types. Separate maps could

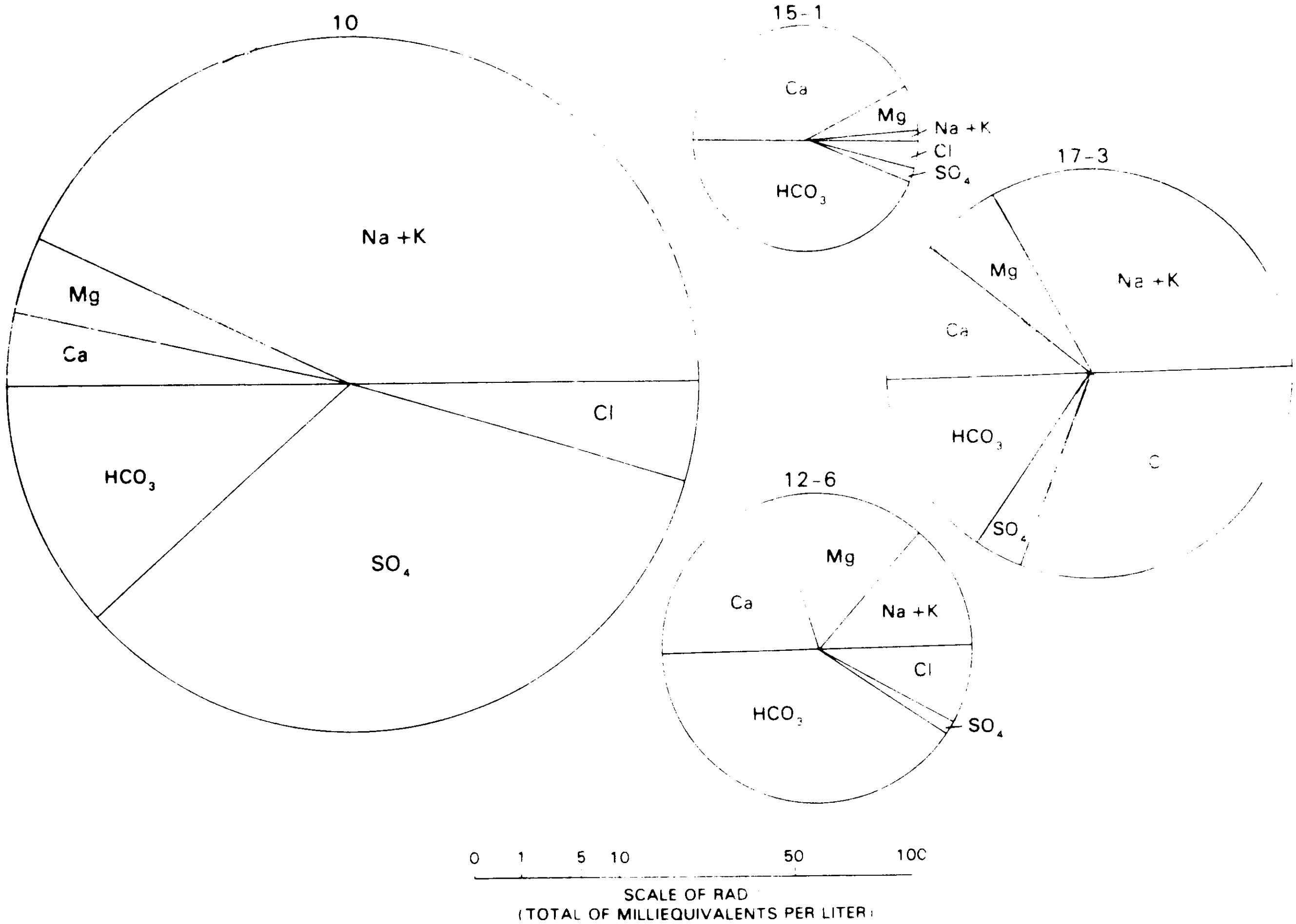
Figure 11A
Bar Diagrams Presenting Data From Chemical Analyses of Water From Three Wells



12-6 = Well Number

Source: Hem, 1992

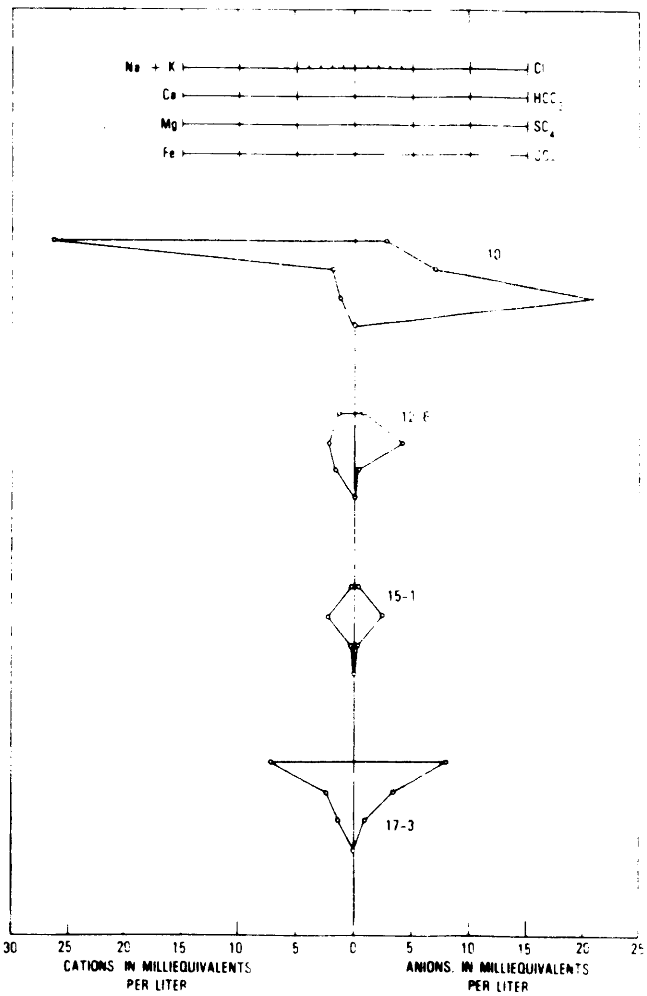
Figure 11B
Circle Diagrams Presenting Data From Chemical Analyses of Water From Four Wells



12-6 = Well Number

Source: Hem, 1992

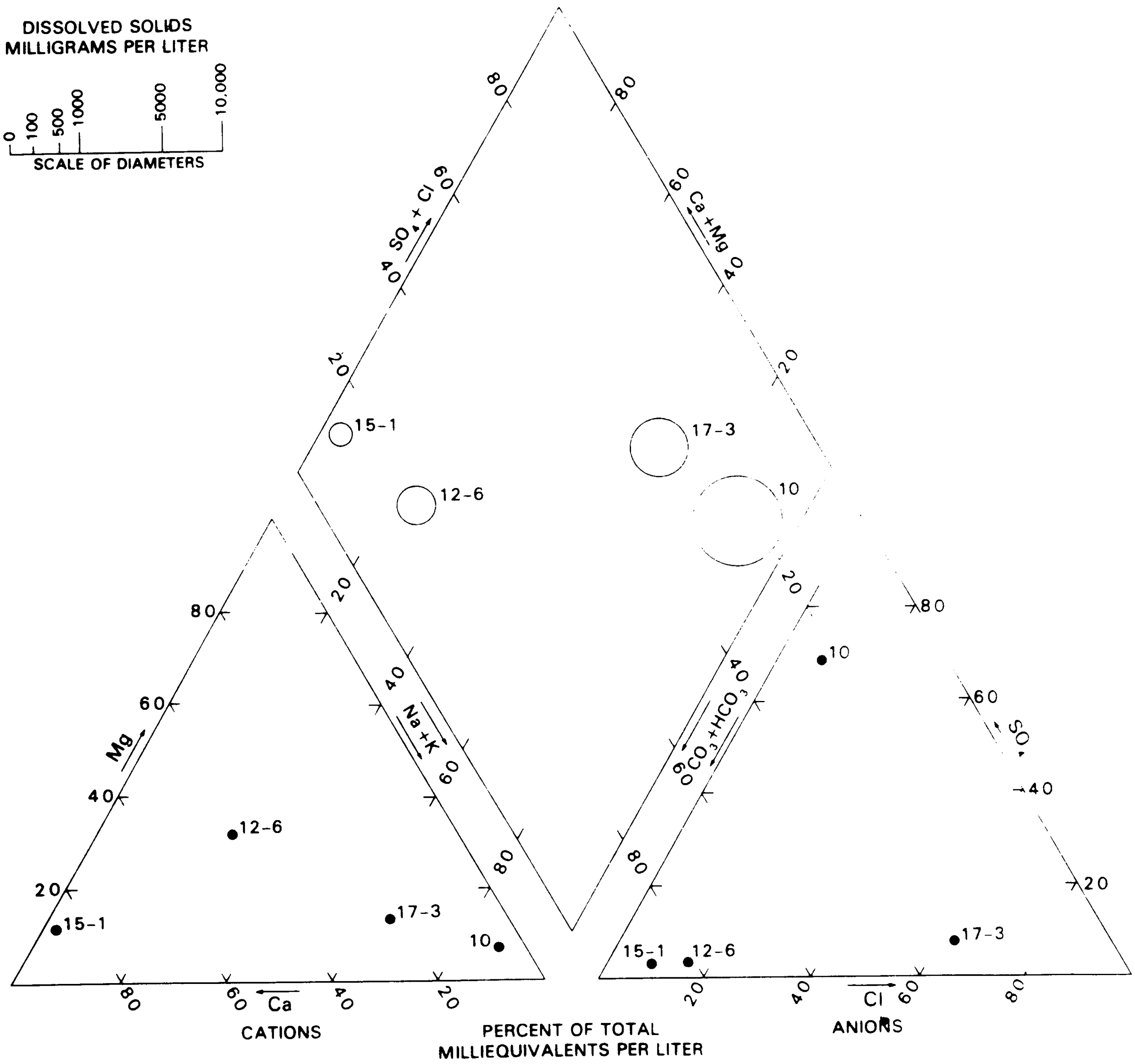
Figure 11C
Stiff Diagrams Presenting Data From Chemical Analyses of Water From Four Wells



12-6 = Well Number

Source: Hem, 1992

Figure 11D
Trilinear Diagram Presenting Data From Chemical Analyses of Water From Four Wells



12-6 = Well Number

Source: Hem, 1992

be made for each constituent of interest for individual aquifers. A GIS may assist ground water scientists in the development of draft maps. Mapping software available for personal computers can assist in the development of simple maps.

Historical data of acceptable quality may be used to identify temporal trends in ground water quality. Geographic trends in ambient ground water quality, or contaminant concentrations, can be analyzed and compared over time to identify areas of decreasing ambient quality due to anthropogenic contamination. Trends in ground water quality may also be used to justify and apply ground water protection policies in specific areas.

Considerations

The monitoring of ground water quality can be highly resource intensive, particularly if new monitoring wells are installed. Labor and equipment necessary to collect samples can be expensive. For most areas, geologic and hydrogeologic assessment programs are conducted in tandem. Therefore, holes drilled for geologic characterization of materials can also be used for installation of dedicated ground water monitoring wells. See Components #1, #4, and #9 for further discussion. Samples should be collected over time and geographic area by identical methods. This will help ensure accurate results and comparability of data. Analysis of ground water samples can be costly, depending on the targeted parameters. Increasing the number of samples or monitoring wells will decrease the level of uncertainty associated with the findings but increase the costs. Developing maps showing lines of equal parameter concentration is interpretive and should rely heavily on the understanding of the flow system. GIS availability may aid ground water scientists in developing such maps.

Background ground water quality monitoring is helpful in determining trends in ground water quality. These trends are useful in forming sound protection policies. Related historical data may provide additional information, but the reliability of the data should be evaluated.

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For More Information

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CHAPTER 3:

Approaches to Assessing Aquifer Sensitivity and Ground Water Vulnerability

As water moves through the hydrologic cycle, its quality changes in response to the environments through which it passes. The changes may be either natural or human-influenced. In some cases they cannot be controlled, but in many instances the changes can be managed so as to limit adverse impacts on water quality.

An understanding of the relationship between aquifers and their recharge areas is critical to evaluating the condition of ground water resources and designing programs for their protection. One means of identifying options for resource managers is to conduct aquifer sensitivity and/or ground water vulnerability assessments. For the purposes of this document, EPA defines *aquifer sensitivity* as:

> the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic materials in question and the overlying saturated and unsaturated materials. Aquifer sensitivity is not dependent on land use and contaminant characteristics.

Ground water vulnerability is defined as:

> the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest under a given set of land-use management practices, contaminant characteristics, and aquifer sensitivity conditions.

Resource managers can use the various methods identified in this chapter to assess aquifer sensitivity and ground water vulnerability. By conducting such assessments, managers can prioritize which areas and which potential sources of ground water contamination need special management attention. Establishing these priorities will allow States to use their often limited financial and personnel resources to achieve maximum environmental benefits.

There are many different sources of ground water contamination. The type of land use in a recharge area may be the most important, as well as the most controllable factor in determining ground water quality. Residential, commercial, and industrial development may pose serious threats to ground water quality due to drastically altered infiltration rates caused either by reducing recharge areas with impermeable pavement or by degrading the quality of water that does recharge.

Residences can contaminate ground water through faulty septic systems, over-application of lawn chemicals, and the improper disposal of household hazardous wastes. Industrial areas may produce chemicals that can percolate to ground water if not managed properly. Accidental spills also can occur, and depending on the contaminant(s) involved and the quantity of the spill, these can seriously contaminate ground water environments. Intensive use of chemicals on agricultural land in areas vulnerable to those chemicals also can pollute ground water. Less intensive land uses and wise, conservative use of chemicals can minimize this contamination.

Management efforts to protect ground water quality may be ineffective in areas with leaking or poorly constructed water wells and abandoned or improperly sealed wells. In either case, properly applied chemicals may leak directly along the well casing, causing rapid degradation of the ground water and posing the more serious problem of cross-contamination of adjacent aquifers.

An analysis of land use, aquifer use, and the relationship of aquifers and their recharge areas can help determine the sensitivity and vulnerability of an aquifer when considered along with the hydrogeologic and hydraulic properties discussed in Chapter 2. The four Approaches to assessing ground water described in this chapter expand on the Components discussed in Chapter 2 by taking into account the use and vulnerability of ground water resources.

These four Approaches follow a rational progression that managers typically use to improve their understanding of ground water sensitivity and vulnerability. That progression is reflected in the organization of this chapter:

- Approach #1 - Aquifer Sensitivity

- Approach #2 - Aquifer Use
- Approach #3 - Land Use
- Approach #4 - Ground Water Vulnerability

Approach #1: Aquifer Sensitivity

Definition

Aquifer sensitivity is the relative ease with which a contaminant applied on or near the land surface can migrate to an aquifer. An aquifer's sensitivity is a function of the intrinsic characteristics of the geologic materials and the overlying saturated and unsaturated materials. Aquifer sensitivity is not dependent on land use or contaminant characteristics.

Objective

The objective of an aquifer sensitivity assessment is to estimate the relative ground water pollution potential of specific hydrogeologic settings. An aquifer sensitivity assessment provides a means to screen a broad geographic area, and to characterize or rank the intrinsic potential for the ground water to become contaminated. Sensitivity assessment methods help resource managers identify critical areas where more detailed mapping or assessments (including vulnerability assessments) may be warranted, select monitoring sites, choose ground water protection management practices, and prioritize areas for enhanced protection. Areas that are assessed as sensitive and that have been subjected to applications of contaminants, spills, or discharges, could be further assessed with a vulnerability method (see Approach #4), and evaluated with a monitoring program.

Data Needs

The specific data needed to assess aquifer sensitivity are dependent on the sensitivity method selected and the scale of the assessment. Typical hydrogeologic factors needed for such assessments include the following (modified from Aller et al., 1987):

- depth to aquifer
- aquifer recharge
- aquifer media

- confining-layer media
- soil media
- surface features
- unsaturated zone
- hydraulic conductivity

Depth to aquifer is the measured distance between land surface and the top of the aquifer. The depth to aquifer is an important element for assessing aquifer sensitivity, because depth measures the thickness of materials through which a contaminant must pass before reaching the aquifer. While not always the case (especially in the semi-arid areas of the Midwestern United States), greater depths to aquifers often imply longer travel times in the unsaturated media, and thus offer a greater distance through which contaminant attenuation may occur. For confined aquifers, the depth is calculated through the overlying material to the top of the aquifer. For unconfined aquifers, the depth is calculated to the water table.

Aquifer recharge is the total amount of water that is applied to the ground surface that infiltrates to the aquifer. Recharge can transport contaminants to the aquifer. The greater the recharge, the greater the potential for ground water to become contaminated; however, recharge may also dilute contamination. The effects of recharge should be evaluated individually for different contaminant sources and hydrogeologic settings.

Aquifer media is the type of material that constitutes an aquifer (e.g., limestone, sand, or gravel) . The aquifer medium determines the path length, route, and rates of travel that water and contaminants would follow, and thus affects the attenuation process. The type of flow path (e.g., conduit, fracture, intergranular) is a significant attribute of the medium that contributes to the aquifer's sensitivity to contamination.

Confining layer media refers to the low permeability geologic materials above and below confined aquifers. The confining layer's thickness, composition, and permeability define the path length, route, and the rate of travel of ground water and potential contaminants through the confining layer to the aquifer. Confined aquifers are less likely to become contaminated by pollutants infiltrating from the unsaturated zone than are unconfined aquifers. The lowest probability of a contaminant reaching an aquifer, or contaminants being transported from one aquifer to another, will occur where confining beds are thick, of very low permeability, not compromised by human activity, and not subjected to fracturing or dissolution features.

Soil media is the upper weathered zone of the earth's surface. Soil media thickness, composition, and permeability have significant impact on the amount of recharge that infiltrates into the ground. In addition, soil organic matter and clays may adsorb some contaminants, reducing the threat of contamination. Slope can also impact the amount of recharge. For a given surficial sediment type, shallow slopes are more conducive to recharge than steep slopes.

Surface features are the geologic and geomorphic features (e.g., sinkholes, fractures, etc.) of the land surface that act as open conveyances to the aquifer. Such features are generally portions of an area's natural infiltration system that can provide easy access of contaminants to the underlying aquifer.

The **unsaturated zone** is the zone of geologic material above the water table and, for purposes here, below the soil zone. The characteristics of the unsaturated zone media affect the path length and attenuation time for contaminants moving through this zone.

Hydraulic conductivity is a quantitative term that refers to the ease with which a fluid (e.g., water) can pass through a given medium. The rate at which the ground water flows also affects the rate at which a contaminant can spread through an aquifer. As the hydraulic conductivity increases, the potential for more ground water to become contaminated also increases.

Methods

Specific hydrogeologic factors, as detailed in Components #1 through #10 above, provide the preliminary basis upon which ground water scientists conduct sensitivity assessments. It is the completeness, accuracy, and detail of these hydrogeologic data that will affect not only the accuracy of the sensitivity assessment method employed, but also the selection of which method is most appropriate.

Methods for assessing aquifer sensitivity use only hydrogeologic factors, such as soil and aquifer physical characteristics. Methods for obtaining these hydrogeological data range from simple searches of published data to complex field data-collection efforts. Typically, the data required to conduct sensitivity assessments already exist and can be collected through a literature search and review of data such as well logs. The literature search should include published and unpublished materials, such as maps, reports, data bases, well logs and monographs. The U.S. Geological Survey (USGS), State geological surveys, State water research and resource agencies, State engineers' offices, the U.S. Department of Agriculture's Soil Conservation Service (SCS), and local and State universities are all good sources of hydrogeological data and may also be able to provide information about available modeling results. County and local planning agencies may also provide supplementary information that may be helpful for site-specific assessments.

A review of available data will help a resource manager determine if more site-specific field data collection efforts are warranted. If further data collection efforts are necessary, an evaluation of the data requirements, the applications and analyses that the data will support, and consideration of the most efficient means of collecting and managing the data will help maximize the use of often limited financial and human resources.

Sensitivity assessments may be conducted using one of two categories of methods -- hydrogeologic setting classification or aquifer sensitivity scoring methods. Hydrogeologic setting classification methods assess sensitivity by delineating subareas within a management area, based on inherent hydrogeologic characteristics (e.g., permeability and texture of geologic materials). Sensitivity characteristics are usually similar within a given subarea. Hydrogeologic classification methods usually use two or more hydrogeologic factors to delineate sensitivity classes. Most hydrogeologic classification methods result in the delineation of between two to five classes of relative sensitivity (e.g., highly sensitive, moderately sensitive). Advantages in using hydrogeologic setting methods to determine sensitivity include the following:

- these methods are based on easily obtainable information from a wide variety of local sources, often without reconnaissance

- these methods are relatively simple to use

- these methods allow comparisons to be made across State boundaries because intrinsic parameters of aquifers and confining beds form the basis of mapping, rather than political boundaries.

Hydrogeologic setting classification methods are most frequently used as a screening tool for broad geographic areas (such as a county); however, the methods can also be used for smaller areas if data sets are of sufficient detail and accuracy. Classification methods are particularly helpful in assessing areas with great variation in the completeness, accuracy, and detail of hydrogeologic data. The user should be aware, however, that results may reflect the biases and capabilities of those conducting the assessment. The shortcomings of the method titled DRASTIC noted by Soller, and discussed at the end of this Approach, also apply to hydrogeological classification methods.

The steps involved in using a hydrogeologic setting classification method generally are as follows:

(1) determine the availability of data for the factors used in the method. Based on the availability, the user may choose to collect additional data, modify the method, or select another method

(2) select the number of aquifer sensitivity classes desired. The selection should be based on the number of plausible management options to be considered and the variety (or range and magnitude) of hydrogeologic settings

(3) specify classification decision rules that define how to assign an overall sensitivity rating to an area with mixed ratings for key factors (e.g., recharge is rated high, soil texture is medium, and depth-to-ground water is low). Decision rules focus on the number of factors, with like-sensitivity ratings necessary to place an area within a class. Because of the relative nature of the class determination, a judgement must be made as to whether all, some, or only one of the classification criteria must be met. The rule-makers should select decision rules that will identify sensitive areas that seem most consistent with ground water protection needs and the local hydrogeology

The following example of a hydrogeologic classification method considers leachability characteristics in Kansas soils. The data base for the study, the National Cooperative Soil Survey, is very detailed. Therefore the method may be used accurately at the field (small area) level. This example has been excerpted from EPA, (in press).

> According to Kissel et al. (1982), many soil materials that overlie aquifers in Kansas offer protection from contaminants that might be transported by infiltrating waters. In some areas of the State, soil materials allow contaminants to reach ground water more easily than in other areas, and the authors devised a classification system to account for the spatial variation in the attenuation potential of these overlying soils.
>
> In general, the greater the percentage of sand in soils (coarse-textured soils), the more susceptible they were judged to be to pesticide leaching. Accordingly, this method grouped Kansas soils into four classes of leaching susceptibility based on soil texture and soil permeability (expressed as the water infiltration rate).
>
> The classification decision rule focused on the limiting soil horizon in the soil profile. For example, a soil with a top layer (horizon) permeability of 1 inch per hour and a subsoil horizon permeability of 4 inches per hour will be placed in leaching susceptibility Class 2, where permeabilities range from 2 to 6 inches per hour.
>
> The final class determination is based on the factor most limiting to pesticide leaching losses -- either texture or permeability. For example, a loam soil with a texture listed in Class 3 but a permeability listed in Class 2 would be classified as Class 3, since Class 3 is less susceptible to leaching.
>
> A leaching susceptibility map of Kansas soils was prepared based on the general soils map available from the National Cooperative Soil Survey at a scale of 1 cm:40 km. An initial attempt was made to classify only those soils with more than approximately 50,000 mapped acres published in Soil Survey reports through May 1981. However, some soils with less acreage were included if they were known to be highly cultivated, particularly if they were Class 1 or 2 soils.

The second method category for assessing aquifer sensitivity is aquifer sensitivity scoring. Scoring methods are an extension of hydrogeologic setting classification methods in that they use relative rankings or ratings to classify the subject area based on hydrogeologic parameters. In the literature, aquifer sensitivity scoring methods are referred to as ranking systems or numerical rating systems. Scoring methods involve calculating a rating or numerical score for subareas within a subject area. The scores provide a relative measure of the aquifer sensitivity among subareas, by translating and then comparing physical information to a factor rating.

Because scoring methods recognize a discrete continuum of aquifer sensitivity, they facilitate differential management measures based on relative hydrogeologic sensitivity. This scoring, or ranking, helps in the evaluation of the relative ground water pollution potential of different hydrogeologic settings. Additional applications for sensitivity scoring methods include prioritizing monitoring programs, identifying data gaps, and evaluating land-use activities.

The steps involved in using an aquifer sensitivity scoring method generally are as follows:

(1) determine the availability of data for the factors used in the method. Based on the availability of these data, the user may choose to collect additional data or select another method

(2) score each factor. The range of each factor is subdivided into discrete hierarchical increments. Unlike hydrogeologic setting classification methods where the increments are assigned one descriptive class, each increment is assigned a numerical value reflecting the relative degree of sensitivity

(3) combine scores to produce an overall sensitivity score for the setting. Each method may use either additive or multiplicative mathematical approaches for combining factor scores into a final score for a setting. Multiplicative approaches are used to weight factor scores relative to the assumed importance of each factor. Output for a sensitivity scoring method typically is a numeric score.

Currently, there are over thirty different documented scoring methods for assessing aquifer sensitivity. Some of these methods allow the user to vary factor input values based on landforms or structural zones of interest. Many of these methods, such as DRASTIC (Aller et al., 1987), include modifications that have been designed to target specific geological or aquifer characteristics of a particular geographic region.

Similar to hydrogeologic setting classification methods, different scoring methods are based on an evaluation of a set of hydrogeologic factors described in the Data Needs section above. Generally, it is preferable that spacially representative data be available for each hydrogeologic factor, although this is seldom possible. It is likely that the accuracy and spatial distribution of data vary according to the factor. As a result, the validity of and confidence about sensitivity classifications or scores will vary spatially. The user must recognize that the level of uncertainty associated with the classifications or scores is generally unknown. Because these methods are primarily for screening purposes, users should conservatively estimate parameter values in the absence of accurate or sufficient hydrogeologic data. For a more extensive discussion of sensitivity methods, including case studies, the reader is referred to (EPA, in press).

Presentation of Data/Information

The output of a hydrogeologic setting classification is typically several class designations of geographic areas (e.g., high sensitivity, moderate sensitivity, low sensitivity) based on the most significant factors affecting contamination potential. These factors may include depth to aquifer, hydraulic conductivity of the aquifer and confining layers, and aquifer recharge (Berg, et al., 1984; Lusch, et al., 1992; Soller and Berg, 1992). Each method may generate a different number of these classes. These outputs can be presented in map, list, or matrix form.

The output for sensitivity scoring methods is typically a numerical score. These scores are dimensionless (that is, not related to an actual physical measurement) and are only a means for developing a hierarchy of relative sensitivity. Resulting scores indicate qualitative rather than quantitative differences in aquifer sensitivity over an area. Two sensitivity scoring methods in use, DRASTIC and SEEPPAGE, use relative ranking systems for seven soil/aquifer parameters to form a numerical index representing an area's relative degree of pollution potential. SEEPPAGE (Moore, 1989) is a relative ranking procedure that assesses the degree of aquifer sensitivity of a site. Table 4 presents a comparison of factors used in DRASTIC and SEEPPAGE.

Table 4
Comparison of Factors Used in DRASTIC and SEEPPAGE

Factors Used in DRASTIC	Factors Used in SEEPPAGE
D - Depth to Water R - Recharge (Net) A - Aquifer Media S - Soil Media T - Topography (Slope) I - Impact of the Vadose Zone C - Conductivity (Hydraulic) of the Aquifer	Aquifer Net Recharge Depth to Water Table Horizontal Distance from Site and Point of Water Use Land Slope Soil Attenuation Potential Soil Depth Vadose Zone Media

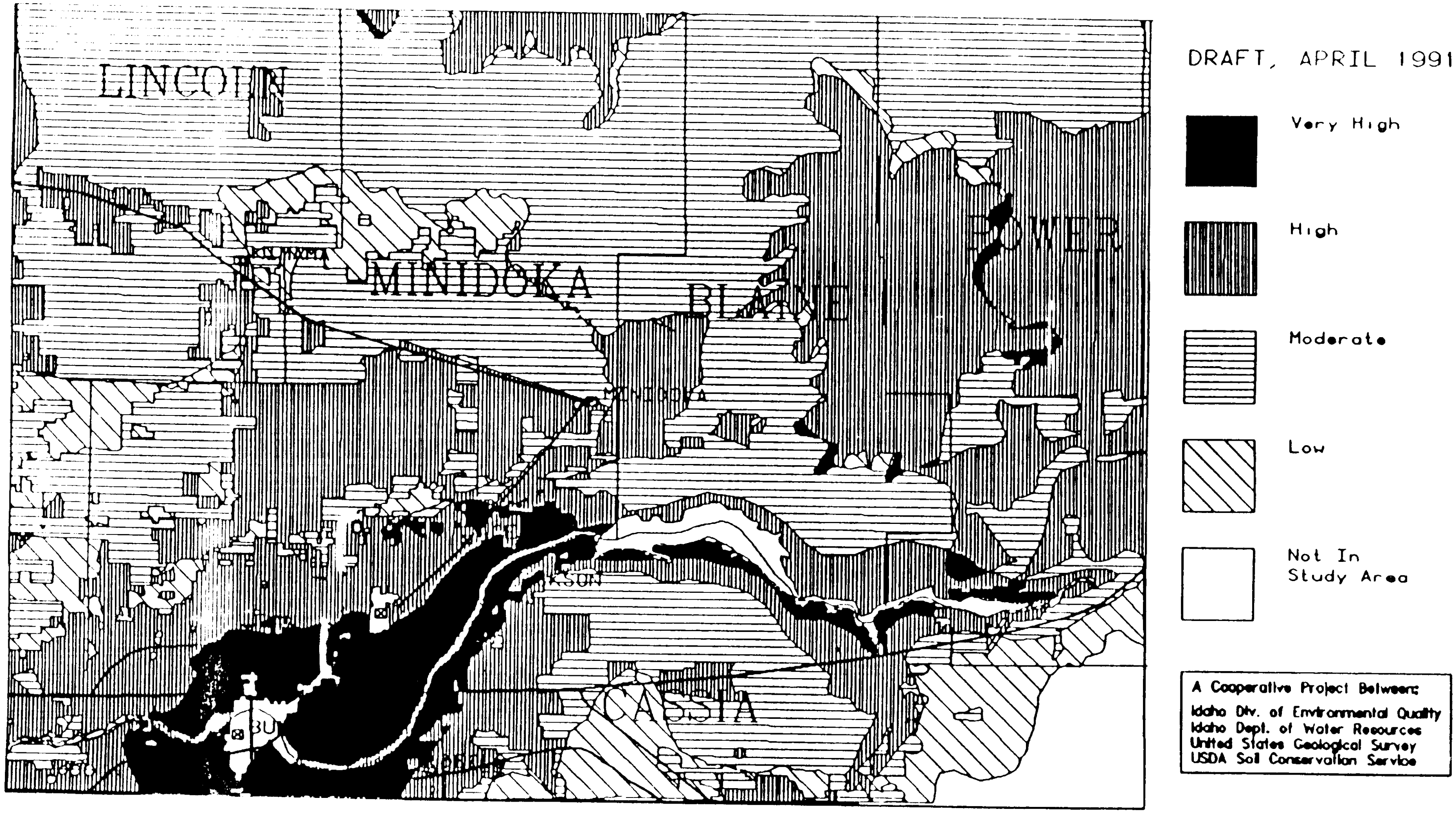
Regardless of whether a hydrogeologic setting classification or a scoring method is employed, a user may prepare a map overlay for each factor using, e.g., different patterns or shades of gray. Superimposing the overlays for all factors will produce a cumulative sensitivity map depicting relative hydrogeologic sensitivity in various patterns or shades of gray. This process can be facilitated by digitizing the factor data into an existing Geographic Information System (GIS). The use of the GIS may also facilitate presentation of several or all of the factors by providing ground water scientists with initial drafts of sensitivity-factor overlays. Figures 12 and 13 present examples of aquifer sensitivity and DRASTIC maps respectively (EPA, in press).

Considerations

Aquifer sensitivity methods are generally used for screening purposes for relatively large geographic areas (e.g., counties). Screening is often performed because the availability of data is limited. Broad-area assessments frequently cannot address the sensitivity of localized aquifers. However, even after large areas with limited data have been screened, resource managers can make conservative assumptions and identify critical areas where future, more detailed studies can be conducted.

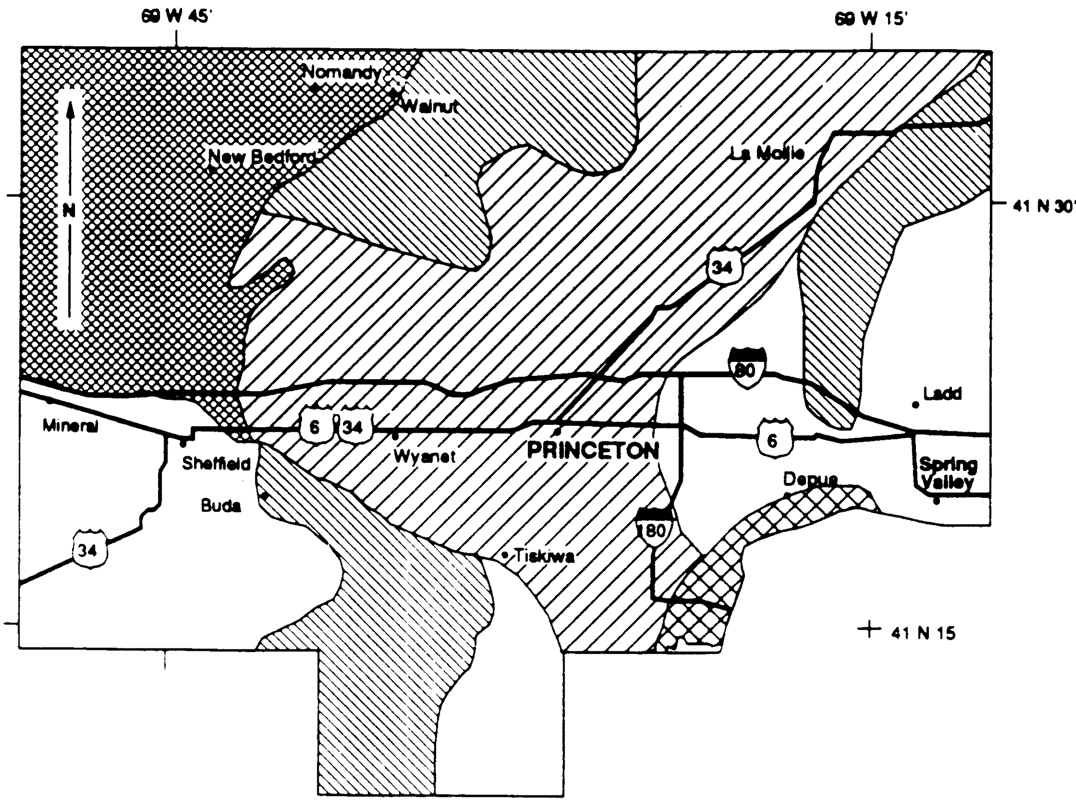
Aquifer sensitivity evaluations should be conducted by using a logical hierarchical approach. Regional studies should be conducted first, followed by more detailed investigations, as needed, in those areas designated on regional maps as being potentially sensitive. Sensitivity mapping should be performed at a scale corresponding to the scale of evaluation.

Figure 12
Map Depicting Relative Aquifer Sensitivity for Lake Walcott Quadrangle, Idaho



Source: USEPA, 1993

Figure 13
Example of DRASTIC Scoring Map of Bureau County, Illinois



Legend	Hydrogeologic Setting	Pesticide DRASTIC Score
	7Ba - Outwash	206
	7I - Swamp/Marsh	149
	7C - Moraine	134
	7D - Buried Valley	126
	7Aa - Glacial Till Over Bedded Sedimentary Rocks	108

Source: USEPA, 1993

Sensitivity classification methods may have inherent drawbacks. The user of any method should be aware that:

- the relations between factors may not be directly reflected in the assessment methods

- factors may overlap, causing some parameters to be represented twice (e.g., including aquifer thickness, permeability and aquifer transmissivity is redundant because transmissivity is the product of an aquifer's thickness and its hydraulic conductivity)

- the capabilities and biases of those conducting the assessment may significantly affect results (e.g., decision rules used to classify areas that have characteristics of more than one class are developed by the user and therefore the user could interject bias into the results).

Resource managers tend to use scoring methods to screen larger rather than smaller areas. As with classification methods, scoring methods allow for the subdivision of assessment areas into subareas, each with its own level of sensitivity. Soller (1992) discusses problems with using scoring methods. He evaluated the DRASTIC scoring method model for the U.S. Environmental Protection Agency (EPA). The following shortcomings of DRASTIC noted by Soller also apply to other aquifer sensitivity scoring methods:

- opportunities for the modeler to err are numerous, because the literature often states that the modeler does not have to be a hydrogeologist. Computation of scores is often complex, involving the gathering and subjective interpretation of sparse data

- source information, upon which factor values are based, commonly are not available, and when available, may not provide adequate source data

- often these methods produce isolated products with little consideration for regional context or consistency from one area to another

Scoring methods are also limited by the fact that they may not include all the significant factors that determine sensitivity. The weights assigned to the various factors have been a subject of controversy in the use of this type of method. The objective of weighting is to acknowledge the importance of the contribution of each factor to overall sensitivity to contamination. However, the exact relationship between factors is seldom fully understood. As with the user of classification systems, the user of scoring systems should be aware of their subjectivity. Results may reflect the capabilities and biases of those conducting the assessment. A final difficulty associated with scoring methods is the uncertainty associated with establishing a score that will trigger the need for ground water protection management responses. Because of the uncertainties associated with aquifer sensitivity methods, managers may choose to be conservative in selecting ground water protection and management practices and in prioritizing areas for enhanced protection when basing decisions on sensitivity assessments.

The resources required to determine the availability of existing data depends on the sensitivity assessment method selected, but consist primarily of professional staff time. Assessments at the 1:24,000 or larger scale (i.e., a small area) often require more data than are generally available. Regional data, however, usually exist to satisfy the data requirements of many of the methods. Because the sensitivity assessment process is used to screen broad areas, additional field collection of localized data, which can be costly, is not usually necessary.

Citations

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Approach #2: Aquifer Use

Definition

Aquifer use is defined as the human activities for which water in an aquifer, or the ground water reservoir as a whole, is used and the quantities of water withdrawn for those activities. Unlike aquifer characteristics, aquifer uses are dynamic and can change significantly over time.

Objective

The objective of describing aquifer use is to account for all existing uses of water from a specific aquifer or the ground water reservoir, quantify ground water withdrawal rates, and identify types and geographic areas of water use. This information is useful for projecting future use trends. Knowledge of current and future use patterns allows managers to plan for changes such as new or modified: operating rules, regulations, ground water allocations, or water resource facilities. Additionally, aquifer-use information can be considered along with aquifer sensitivity and vulnerability characteristics to develop water-use strategies that protect aquifer quality.

Data Needs

The data needed to characterize aquifer use and to make projections for future use center on a comprehensive inventory of all wells. The data needs include:

- number and areal distribution of wells for each aquifer
- withdrawal rates of wells
- uses of the water
- economic and demographic characteristics and trends

The **number and areal distribution** of wells can be coupled with demographic data to provide a rough estimate of aquifer-use rates. Because a well that is improperly installed and/or poorly maintained can act as a vertical conduit for the migration of contaminants to the ground water, ground water in areas with a high density of wells may be particularly at risk from contamination.

The **withdrawal rates of wells**, (i.e, quantity of water pumped over time), can be combined with information on the areal distribution of wells to identify withdrawal-rate density throughout the reservoir or for specific aquifers. It is important for ground water managers to understand the effects that pumping characteristics can have on ground water quality. For example, excessive pumping of a coastal, fresh-water aquifer lowers the potentiometric surface or water table, and enables saltwater to intrude into the aquifer.

Pumping can draw not only ground water, but also contaminants, within the zone of influence of a well, towards the well. This migration of contaminants can extend a contaminant plume in both the horizontal and the vertical directions.

Major **water uses** can be categorized as follows:

- public supply (can include some of the uses below)
- rural, residential, and domestic (generally pumped from individual wells for household purposes)
- commercial (e.g., for hotels, restaurants, office buildings)
- irrigation (e.g., for crop production, parks, golf courses)
- livestock (e.g., for stock wells, feedlots, dairy operations, agriculture)
- industrial (e.g., for fabrication, processing and cooling)
- mining (e.g., for extraction of minerals, coal, gas, petroleum, etc., and for quarrying, dewatering, milling, etc.)

- power generation (water used in the process of generating power)

In addition, ground water can be used to support aquatic ecosystems, a use that does not involve water withdrawals.

Coupling current and historical water-use information with location information can facilitate understanding of water-quantity demands across the areal extent of an aquifer or the ground water reservoir as a whole. In forecasting future water-use patterns, information on **economic and demographic characteristics and trends** is essential. Such information includes growth statistics on population, the economy, per-capita energy consumption, food-production demands, manufacturing, mining, government programs (e.g., environmental protection, agricultural subsidies), technological changes, and the price of water to users (Viessman and Welty, 1985). Some of these trends are discussed in Approach #3.

Methods

Methods available to assess aquifer use can be divided into the following two categories: (1) methods to establish current use patterns; and (2) methods to identify trends in future use.

Well permit records represent a key source of data for aquifer-use characterization. Health departments, State geological surveys, and/or State water research or resource agencies, typically maintain a file of permits for wells. These permits may stipulate the maximum withdrawal rate for a well, and/or may specify the type of use for the water. This information can be used to develop a relatively comprehensive characterization of aquifer-use patterns.

In addition to permit files, some States maintain well data bases. Such data bases are often routinely updated, but the level of detail contained in them varies significantly. For example, some user classes may be exempt from permit or reporting requirements (e.g., small users using less than 5,000 gallons/day), or the source aquifer may not be specified.

It is virtually certain that aquifer-use patterns will change with time. Historical use data help to project future trends. These data highlight the principal factors influencing water use and indicate how changes in these factors have effected use in the past. To aid in developing aquifer-use strategies, estimates of future demands should be coupled with current and historical use data.

Changes in use patterns will differ by use type. For example, suburban population changes will significantly affect residential water use; change in a regional economic base from agricultural to manufacturing will change the amounts of irrigation and industrial water demand.

Projecting future use trends usually involves the use of growth models that incorporate information on economic and demographic growth trends. The simplest model would associate an economic or demographic indicator element (e.g., population) that is assumed to be directly, linearly related to a specific water-use type. A growth multiplier of the indicator element, for a specified time span, is then applied to the water-use type. More complex models are based on mathematical relationships between economic and demographic indicator elements and the types of aquifer uses.

Presentation of Data/Information

A variety of formats can be used to present aquifer-use information, including tables, graphs, maps, or reports. The elements presented under any of these formats parallel those outlined in the Data Needs section of this Approach. Graphs and maps provide a good format for easy interpretation of aquifer-use data. Place markers of various size circles can be assigned to wells according to their withdrawal rate. These place markers can also differentiate water-use types by color. Maps of this information depict water-use and withdrawal patterns.

In addition to displaying well-discharge and water-use information, maps can integrate aquifer-use data with other aquifer and demographic data. Geographic Information Systems (GIS) can integrate these data, and provide initial displays of withdrawal patterns in relation to demography, industrial activity, land use, etc.

Considerations

Managers should consider data availability, limitations of trend projections, and resources required, when characterizing use patterns. Characterizing aquifer use by inventorying all wells may be extremely resource intensive. Moreover, it is unlikely that information is available about all wells, and available water-well permit information may be unreliable. If multiple aquifers exist, it may be very difficult to discern the aquifer in which a well is completed. Geologic and hydrologic characterization of the aquifer or aquifer system (See Components #1 and #2) should be initiated prior to determining water-use trends.

When defining data needs and developing aquifer-use information, it may be useful to first identify critical geographic areas. The determination of such areas can be made based on aquifer vulnerability and sensitivity mapping (See Approaches #1 and #4), preliminary information about general use patterns, and expected regions of industrial or population growth, etc. Using this approach, use patterns in areas of concern can be addressed first.

Numerous data gaps exist in water withdrawal information. Reasons for these gaps include: use classes being exempted from reporting requirements, small-quantity users not needing a permit, and some land uses (e.g., parks) receiving little investigative attention.

Estimates of those economic and demographic trends that influence aquifer use may not adequately account for future changes in regulations, technology, behavior, available resources, etc. Modelers should use data from outside their study area with discretion, understanding that national or regional trends may not be analogous to local trends. Further, the underlying assumptions used to develop trend projections must be met.

One option that may reduce the risk of erroneously projecting future use trends is to develop a series of projections based on a range of scenarios. Some of the scenarios may then be eliminated at an early stage when actual behavior and activities are observed. This approach, however, may require greater initial resources.

Estimating future use trends is dependent on the availability: of adequate data, of staff with expertise in economics and demographics, and of appropriate computer equipment and models.

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Approach #3: Land Use

Definition

Land use is the altering, or maintaining, of existing natural features of the land to meet human needs. Features that may be part of a land-use inventory include hydrologic units (e.g., wetlands, streams, rivers, and lakes), vegetative cover (e.g., croplands, forests and grasslands), and urbanized areas as shown on contour maps.

Objective

Information on past and present land cover, and past, present, and planned future land use is needed to establish land-use trends over time. Determining land-use trends is essential for evaluating future demands on, and degradation of, ground water resources. For example, as land is converted from rural to urban use, the amount of precipitation runoff increases, because more land surfaces become paved and less permeable. Surface water, and potentially ground water, may become contaminated by non-point source contaminants if the runoff is not properly controlled and managed. In addition, the water supply needed to support the increased population must be evaluated to determine what, if any, water will have to be imported to meet the new demand.

Data Needs

The data and information needed to establish land-use trends include the following:

- land cover
- land uses
- demography

Land cover data describe the appearance of the land surface, that is, whether the surface is covered by: forests, croplands, grasslands, or water, etc. Comparing past and present land cover provides information on the effect of natural and human changes on the landscape.

Land-use data reflect anthropogenic uses of the land surface. Land uses can be subdivided into four broad categories: urban, rural, agricultural, and open space (e.g., forests, lakes) not included in the other uses. Subcategories, dependent on the purpose of the data gathering, are frequently specified. Industrial development (see below) can be located in any of the other categories.

Urban areas usually consist of core cities, containing high-density residential, commercial, and industrial areas, surrounded by suburbs with lower-density residential and commercial areas. While many urban areas in the United States depend on surface water for the majority of their drinking water supply, a combination of surface and ground water sources is often used. Some cities such as Miami, San Antonio, and Memphis rely on ground water as their primary drinking water source (Spirn, 1984). With population increasing in urban areas and surface water availability remaining constant, ground water will probably become more important as a source of drinking water.

Urban land use produces more runoff of precipitation than any other type of use. Roads, parking lots, buildings, and sidewalks all decrease the permeability of the land surface, and therefore decrease the amount of infiltration, and ultimately ground water recharge to an underlying aquifer that would occur under natural conditions. This decrease in recharge could affect future availability of ground water.

Rural areas contain low-density residential land-use areas and open spaces intermixed with slightly higher densities of residences at crossroads and small towns. A majority of people in rural areas rely on ground water as a primary source of water (USEPA, 1990). Ground water supplies are usually adequate to support an individual water well in sparsely populated areas. However, the individual sewage disposal systems found in rural areas are conducive to contamination of shallow aquifers.

Agricultural areas have low residential density and can be described as cropland, livestock, silviculture, or fallow. Agricultural activities can result in the alteration of surface-drainage patterns. For example, forests or grasslands that are cleared for agricultural purposes produce more runoff of precipitation than would occur under natural conditions (Marsh, 1983). Agriculture can also impact water quality; application of agricultural fertilizers and pesticides can contaminate both ground and surface water.

Industrial land use usually occurs near available natural resources (e.g., metals, fossil fuels, or water) needed by the industry, or near major transportation corridors (i.e., highways, rivers, lakes, airports). Point-source pollution (e.g., leakage from chemical storage, or untreated water discharged into surface water) from industrial sites may impact the quality of local ground water (USEPA, 1989a). In addition, industry often uses large quantities of ground water for manufacturing. For more information about aquifer use, see Approach #2.

Demography is the study of the size, density, distribution, and characteristics of human populations. Census data show areas of gaining or losing population at small to regional scales. As population grows, so do the conflicts between supply and demand for water, and residential versus industrial development. Each land use has associated with it a potential for ground water contamination. Ground water protection policies and strategies should be developed in growth areas prior to the realization of degraded water quality or insufficient water supplies to meet demands.

Methods

Analysis of land-use trends should rely on collection and interpretation of existing data. Land-cover and land-use data are typically available from various Federal, State, and local agencies. Demographic data can be obtained from local governments or directly from the Census Bureau. Other data can be collected from the following:

- the U.S. Geological Survey (USGS) and State geological surveys (topographic and land-use maps, aerial photographs and satellite imagery)

- the U.S. Bureau of Land Management (land-status maps)

- the U.S. EPA (contaminant-source information)

- U.S. Department of Agriculture's Soil Conservation Service (SCS) (soil-survey data and maps)

- U.S. Bureau of Census (census information)

- relevant State agencies (land-use maps and data bases)

- local planning agencies (zoning maps and comprehensive plans)

Topographic maps from the USGS provide elevation, cultural, and hydrographic data at a variety of scales. The scale of the most detailed and common USGS map is 1:24,000. The maps may also identify areas of vegetative cover. Topographic maps should be used for outlining vegetative areas only in the absence of more reliable and detailed sources such as recent aerial photographs. Topographic maps also show the extent of urban development; however, they are updated infrequently and should not be used for this purpose. The USGS also produces land-use maps. These maps show land use and land cover (as polygons) for regional areas at a scale of 1:100,000 or smaller (i.e., larger geographical area). These maps can be used for regional assessment of land-use characteristics, but should not be used to evaluate local land uses. More detailed information for local assessments may be available from local planning agencies.

State agencies, sometimes in cooperation with Federal agencies, may maintain land-use maps for parts of their State. For example, Nebraska's Natural Resources Commission, Databank Section, in cooperation with the SCS, is developing State land-use maps for individual counties. The Databank Section maintains computerized copies of the maps and SCS maintains the actual data. Land-use maps currently exist for 61 of Nebraska's 93 counties. The information contained on the maps includes different types of crop lands, pasture land, forests, urban areas, and surface water bodies. Also, Florida's State Planning Law of 1986 requires all counties to develop comprehensive plans that include land-use maps. Florida has five water-management districts all or some of which have developed land-use maps for their own districts.

Aerial photographs and satellite imagery can be used to identify land uses. These remotely sensed images can be particularly useful for quickly surveying the land cover and land use of relatively large geographic areas. Conventional aerial photography is typically used to obtain relatively large-scale, land-use assessments of such features as: forests, agricultural lands, paved or roofed areas, and industrialized areas. The U.S. Department of Agriculture's Agricultural Stabilization and Conservation Service (ASCS), and the USGS, through their National High Altitude Aerial Photography (NHAAP) program, regularly take aerial photographs on a county-by-county basis. The USGS NHAAP program takes photographs on an approximate five-year basis to update 7.5-minute topographic maps. The ASCS aerial-photography program generally takes photographs on a county-by-county rotational basis for use with the SCS soil-series maps. The scale of aerial photographs in the range of 1:12,000 to 1:50,000 are often used for mapping land use and may be obtained from the USGS or the Aerial Photography Field Office of the ASCS. Digitized cultural data are available for roads, utilities, county boundaries, and other manmade structures, in computer files that may be used in a Geographic Information System (GIS). Some local-planning agencies also maintain aerial photographs of their jurisdiction.

Satellite or other remotely sensed images typically are used for defining large features such as slopes, drainage, and geology, and for assessing spatial relations of natural and anthropogenic features on a broad range of scales (Marsh, 1983). These images can be used to enhance field surveys. Satellite images provide the user with the ability to observe relatively large areas (e.g., 115 square miles for Landsat MSS) and to observe the spectral reflectance of several bands or wavelengths of electromagnetic energy. The various bands of spectral reflectance recorded on the image allow the user to "highlight" various physical features on the land surface. For example, if the image is displayed in the near Infrared (band 6 Landsat TM), vegetation will appear darker than the surrounding features, while developed areas will appear very bright.

Satellite imagery generally comes in digital (i.e., electronic tape or diskette) format, but may also be purchased in picture scenes. Image processing software can be used for both aerial photography (if scanned into digital format) and satellite images. Image processing software can be used to enhance the image to highlight various features and to digitize different spatial land-use patterns for use in a GIS.

Zoning ordinances and corresponding zoning maps can provide a wealth of information on land use in developed areas. In their simplest form, zoning ordinances aim to control the general types of activities that can occur within a specified area (USEPA, 1989b). For example, an area may be zoned for open spaces, agricultural, residential, commercial, light industrial, or heavy industrial use. Zoning maps may present existing development or areas legally planned for development that has not yet occurred. Comprehensive plans designed by local planning agencies establish goals for, and define the geographical area of, future development. These plans often contain generalized maps that highlight areas of potential growth. Parcels of land within a growth area that is presently zoned for rural use may be rezoned to a use compatible with a comprehensive plan.

Survey plat maps of property boundaries are very useful in showing urban land-use changes. These maps are available for most cities in the United States and were developed for tax-assessment purposes. Survey plats show streets and historical uses, making these maps very helpful in locating sites where potential contaminants may be buried, but not readily apparent because land-use changes have masked former uses. By comparing current and past plat maps, new development can usually be identified. Local property records also document past and present land uses. Such records include land titles, deeds, property transfers, and building permits. Property transfer records typically are maintained at the county level. These records should also provide good information on past, present, and future land uses.

For many years, the SCS has been providing technical and scientific support to local governments in producing soil-survey maps and reports. Soil boundaries are often mapped on aerial photographs that show land cover and uses. The land-use and land-cover information contained on the photos may be outdated, but may provide historical information in establishing land-use trends. The soil information is also helpful in identifying environmentally sensitive areas such as hydric soils that may indicate the presence of wetlands. Many local governments have updated original soil surveys with new field information and put the surveys on new base maps.

Federal and sometimes local floodplain maps depict floodplain boundaries and can be used to protect these sensitive areas. Other environmentally sensitive areas, such as wetlands, riparian zones, and ground water recharge areas, can be identified and mapped. These maps could be consulted in the development or modification of zoning regulations and comprehensive plans.

Some jurisdictions peripheral to urban areas, have developed methods of ensuring an adequate supply of ground water, as their population expands. For example, in addition to customary approval of wells and on-site sewage disposal systems, officials in Loudoun County, Virginia review detailed hydrogeological studies of available ground water before they will approve of plans for subdivisions of ten or more lots (Cooper, et al, 1989). This development standard has been an effective means of ensuring available ground water supply prior to development.

Presentation of Data/Information

Information obtained from land-use and land-cover assessment methods should be assembled onto a base map. Most urban jurisdictions maintain detailed base maps of their land areas, but in the absence of a detailed base map, USGS topographic maps can be used. Data on: existing land cover, land uses, environmentally sensitive areas, zoning, and potential growth areas, could be mapped. Maps could be overlain (manually, or with a GIS if the data are digitized) for management planning and protection purposes. The overlays are easy to read and can serve as excellent exhibits for presenting information to decision-makers.

Considerations

Existing aerial photography and satellite imagery are excellent tools for determining land-use distribution, and are very inexpensive. Aerial photographs can be purchased from Federal agencies (e.g., ASCS or USGS) for regional studies. Satellite imagery can also be purchased from private firms and distributors. Many universities possess the necessary image-processing software, hardware, and expertise to assist States in assessing land-use patterns and trends.

Although zoning information provides local land-use data of significant detail on current and past land uses and is easy to obtain, local planning agencies should be consulted to ascertain that the information is not out of date. Zoning ordinances and comprehensive plans are updated approximately every ten years by local planning agencies, or more frequently as local conditions warrant. Zoning maps are usually updated after a rezoning occurs for a given property.

The ultimate products of an assessment of land cover and land use are informed predictions regarding land-use trends and better planning for future land-use protection measures. Ground water protection policies aimed at controlling land use can be implemented using a variety of tools, including comprehensive plans to define goals and zoning ordinances to set development standards. These planning tools can help protect ground water resources by targeting land uses that have a high potential to contaminate the ground water.

Citations

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Approach #4: Ground Water Vulnerability

Definition

Ground water vulnerability is the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest under a given set of land-use management practices, contaminant characteristics, and aquifer sensitivity conditions. The concept of vulnerability focuses on the vertical migration of contaminants into the ground water reservoir, rather than on the direct placement of contaminants into the reservoir (e.g., backflow of chemicals down the well during chemigation practices). Ground water vulnerability assessment methods assess hydrogeologic characteristics, contaminant characteristics, and management practices related to the use of contaminants. For example, aquifers with a high degree of sensitivity and located in agricultural areas with high pesticide use are likely to be vulnerable to contamination.

Objective

Assessing ground water vulnerability provides a means of accounting for the interrelated processes governing the movement and degradation of contaminants in the saturated and unsaturated zones. Vulnerability assessment methods are used to identify ground water resources that are at risk of being contaminated and serve as an aid in the selection of appropriate ground water protection and management practices.

Data Needs

The data needed to assess ground water vulnerability include the following:

- aquifer sensitivity (i.e., hydrogeologic characteristics)
- potential sources of ground water contamination and their characteristics

- land use

Analyzing an **aquifer's sensitivity** is a useful preliminary step in assessing the vulnerability of ground water resources. An analysis of aquifer sensitivity provides ground water managers with information concerning the intrinsic characteristics of the materials comprising the aquifer and its overlying materials. That information provides a basis upon which ground water scientists can perform ground water vulnerability assessments to estimate the relative ease with which specific contaminants can migrate to an aquifer. For more information on aquifer sensitivity analysis, including the uncertainties associated with its use, see Approach #1.

To estimate the vulnerability of an aquifer, managers need to know the locations and types of **potential sources of ground water contamination**. In the absence of current or potential sources of contamination, ground water is not considered vulnerable.

Potential sources of ground water contamination can be categorized as point and non-point sources. Point sources are any discernable or discrete conveyance from which pollutants are or may be discharged (USGS, 1989). Point sources include: municipal and hazardous-waste landfills, underground storage tanks, septic-tank drainfields, accidental spills, leakage from chemical-storage areas at industrial and commercial facilities, and leakage of petroleum products from underground storage tanks.

Non-point sources are releases of contaminants that occur over a wide area. Contamination from dispersed sources cannot be traced back to a single point of release. Non-point sources include pesticides and fertilizers applied in agricultural areas, and runoff from city streets and parking lots.

The toxicity and quantity of potential contaminants from point and non-point sources determine the severity of ground water contamination. Common ground water contaminants include:

- organic chemicals
- inorganic chemicals (including metals)
- radionuclides

- microorganisms

Common organic chemical contaminants include: trichloroethylene and trichloroethane used as industrial solvents; benzene, a solvent and additive in gasoline and diesel fuels; pesticides such as insecticides, fungicides, herbicides, rodenticides, and nematicides; PCB's used in insulating fluids in closed electrical systems; and other chemicals used for lubricants, dyes, and adhesives. Inorganic contaminants include aluminum, arsenic, cadmium, lead, and mercury, used in paints, protective coatings, alloys, and photography. Other inorganic contaminants include nitrates from human and animal waste and commercial fertilizers, and chlorides from chemical manufacturing, highway de-icing, water-purification processes, and salt-water intrusion.

Radionuclides commonly found in ground water include uranium, radium, radon, cesium, and tritium. Most occurrences of radionuclides in ground water are from natural sources, but in some instances radionuclides are derived from human activities such as medical applications, nuclear fuel-cycle and power-plant operations, mineral extraction processes, and weapons production and testing. Microorganisms that can contaminate ground water include giardia, salmonella, typhoid, and viral hepatitis. Any agricultural activity involving animal wastes has the potential to contaminate ground water with microorganisms.

Because of synergistic effects, mixtures of contaminants may provide a greater potential for pollution than individual contaminants. The chemical and physiochemical reactions among contaminants, water, and geologic materials are not well understood and add a complicating factor to vulnerability assessments.

To a large extent, **land use** determines the number and type of potential sources of contamination. Ground water managers can identify, on a broad basis, where potential sources of contamination are likely to exist by considering land uses. For more information on land use and its impact on ground water, see Approach #3.

Methods

Methods for assessing ground water vulnerability can be divided into the following four major categories:

(1) simulation methods

(2) pesticide leaching methods

(3) contaminant loading methods

(4) mapping methods

For an extensive discussion of the vulnerability assessment methods in categories (1), (2), and (3), including case studies, the reader is referred to EPA's document A Review of Methods for Assessing Aquifer Sensitivity and Ground Water Vulnerability to Pesticide Contaminants (EPA, in press).

Most methods used to assess ground water vulnerability are simulation models that utilize computers. Simulation models are theoretically-based, mathematical expressions of one or more processes or phenomena related to the transport and fate of contaminants in the soil/aquifer systems. Simulation models can be effective in identifying best management practices and in understanding the fate and transport processes that lead to the contamination of specific sites. They can also be used to predict contaminant concentrations, loadings, and the time it takes specific contaminants to travel various distances through the aquifer. Vulnerability simulation models vary primarily by the number of processes incorporated into the computer programs and the number and kinds of input required. Some relatively simple ground water simulation methods incorporate only a few fate and transport processes and can be used on personal computers without extensive technical support. Other ground water simulation models might be referred to as research tools, because they require powerful computers, substantial technical support, and several data bases to operate.

Pesticide leaching assessment methods, the second group of vulnerability assessment methods, are a narrowly-defined subcategory of vulnerability assessment methods that incorporate both hydrogeologic and chemical factors. These methods require both compound-specific and soil-specific information. Pesticide leaching methods allow users to compare the relative leachability of various compounds for a given soil series and set of field conditions. These methods are similar to scoring methods for aquifer sensitivity analyses (see Approach #1), because they calculate a relative index, score, or classification. However, chemical leaching assessment methods incorporate chemical characteristics such as the half-life of the compound and are considered a blend of aquifer sensitivity and ground water vulnerability assessment methods.

The third group of ground water vulnerability assessment methods provides estimates of contaminant loading. Contaminant loading methods combine chemical use (i.e., loading) data with an aquifer sensitivity assessment. Contaminant loading methods can be used to screen large study areas.

The fourth ground water vulnerability assessment method is mapping. Mapping can be used to determine the potential for contamination from point or from non-point sources of contamination. Vulnerability mapping methods are relatively simple, use verified and easily obtainable data, and have as output maps that are easy to interpret. For assessing vulnerability to agricultural chemicals, agrichemical sales data or data on the percent of intensely farmed land per political division can be used and reflect agricultural management practices. For assessing vulnerability to point sources of contamination, the locations of, for example, waste generators, landfills, and abandoned hazardous waste sites are needed.

Shafer (1985), and Bhagwat and Berg (1991) present a procedure for using the mapping method to determine ground water vulnerability. Under this procedure, geologic sensitivity based on a classification method is combined with information detailing the distribution of waste sources per unit area (e.g., county, zip code). Highly vulnerable areas have aquifers located at or near the land surface and contain either numerous contaminant sources or are intensively agricultural. Low-vulnerability areas contain few contaminant sources or are less intensively agricultural, and have either deep or no aquifers. For each study area, the percent of land in each vulnerability ranking is calculated to obtain a weighted vulnerability average. This method is particularly useful for assessing regional vulnerability and for comparing the vulnerability of regions. The method can also be used to identify potential "hot spots" that warrant more detailed investigations. Environmental officials in Illinois used this mapping method to delineate ground water protection planning regions (see the case study on Illinois in Appendix B for more information on this application).

Presentation of Data/Information

Information developed from vulnerability assessment methods can be presented in tabular, graphic, map, or report form. Tables are especially useful for reporting numerical values, such as model output, that represent various degrees of ground water vulnerability. Results from vulnerability assessment methods such as pesticide leaching methods that generate a vulnerability score, classification, or relative index, typically are presented in tabular form. Graphs can be used to illustrate vulnerability assessment outputs for such important relationships as contaminant concentrations in soil versus soil depth.

The results of ground water vulnerability assessments may also be displayed on maps. Small-scale maps (e.g., 1:100,000 or 1:250,000) are often used by managers who (1) are responsible for ground water resources on a county or region-wide basis, (2) need a screening assessment before proceeding to more detailed studies of priority areas, (3) expect to encounter only a limited range of hydrogeologic conditions within a region, or (4) do not have data to conduct a more detailed assessment. The scale of these maps is critical to ensuring that the maps can provide support for their intended uses. Managers should be cautioned that maps may have inherent limitations with respect to their accuracy of representation.

As discussed above, assessing ground water vulnerability requires the synthesis of different types of data, such as:

- aquifer sensitivity (hydrogeologic characteristics)
- land-use and zoning maps identifying potential sources of contamination
- property boundaries
- contaminant (e.g., pesticides) use and physical/chemical property information

If the data are georeferenced, a Geographic Information System (GIS) can help synthesize and overlay the data and provide the ground water scientist with initial drafts of vulnerability maps.

Considerations

Managers should be aware of a number of considerations in the use of ground water vulnerability assessments. Most important are: the uncertainty related to mapping, the inherent limitations on models, and the resources required to implement vulnerability assessment methods.

Mapping uncertainty is a consideration in the use and development of all maps, including vulnerability maps. This uncertainty is often related to the scale of the map. The accuracy of maps is also significantly reduced when a map compiled at a smaller scale (i.e., large geographical area) is displayed at a larger scale (i.e., small geographical area). This is a particularly important consideration when using a GIS, due to the ease with which these systems enable users to enlarge maps. When selecting a map scale to display results, it is important to carefully consider the scale necessary for the intended use, the scale at which data was calculated, and the density of data points.

Assessment methods that rely on simulation models have a number of limitations of which managers need to be aware. The most important of these limitations, and the related questions that managers should discuss with ground water scientists, are as follows:

- Assumptions - On what assumptions is the model based? Have the model's assumptions been met? What is the range in application of the model, physiographically and with regard to specific parameters?

- Input parameters - How reliable are the estimates of the input parameters? Are the input parameters quantified within accepted statistical bounds?

- Quality control and error estimation - Has the model been checked against direct applications or simulation of controlled experiments? (USEPA, 1987)

The costs of staff, computing facilities, and specialized data-presentation equipment needed to support assessment models can be significant. Vulnerability simulation models generally require a high level of expertise, although some models are less complicated than others. Comprehensive simulation models may require a multidisciplinary team of highly-skilled specialists. Even with less complicated simulation models, the use of personnel familiar with them is necessary. Although data requirements vary by the complexity of the model, most simulation models require site- and contaminant-specific values. For the most accurate results, users should have a good basic knowledge of soil science, geology, chemistry, and the hydrogeology of the study area. As a result of these personnel needs, costs are generally greater for technical staff than for equipment or software.

The cost of conducting an assessment using the vulnerability mapping method can also be high, because the method involves many steps, including the gathering of information on hydrogeology and ground water quality (i.e., Components 1 through 10), inventorying potential sources of contamination, and integrating the information. The cost is directly related to the amount of data that are readily available.

Citations

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For More Information

For more information on this subject see the following references:

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APPENDIX A:

Comprehensive State Ground Water Protection Program Priority-Setting Characteristics to be Addressed in Ground Water Resource Assessments

The Final Comprehensive State Ground Water Protection Program Guidance (USEPA, 1992) identified the characteristics below to be used in setting priorities, determining appropriate remediation methods, and making siting decisions. The Ground Water Resource Assessment Document incorporates these characteristics and reorganizes and expands on them where appropriate to provide a comprehensive approach to assessing the resource. This list is included only for reference purposes. It is acknowledged not to be exhaustive but rather suggestive of the kinds of information useful in resource assessment as one of the bases for setting priorities for State ground water protection activities.

- intrinsic sensitivity, hydrogeologic regimes and flow patterns (e.g., recharge and discharge areas), geologic and hydraulic parameters and local hydrogeologic setting
- quantity and potential yield
- ambient and/or background water quality as determined by monitoring
- potential for remediation where contamination already exists
- current use
- reasonably expected future use based on demographics, land use, remoteness, quality, and availability of alternative water supplies
- values attributed to ground water resources

- the interactions and potential contamination impacts between surface and ground water and the value of ground water quality to the maintenance of ecosystem integrity

- inter-jurisdictional characteristics

APPENDIX B

Case Studies on the Development and Use of Ground Water Resource Assessments at the State, Local, and Federal Level

This appendix presents five case studies that illustrate the nature of resource assessment and the variety of approaches for conducting resource assessments in the field. Each case study demonstrates how a State (or as in one case study, the U.S. Department of Energy [DOE]) actually conducted a ground water resource assessment, identifies the parameters included in the State's resource assessment, and demonstrates how the resource assessment was or will be used for decision-making. Each case study includes the following sections:

- Purpose of the Resource Assessment. This section briefly discusses the State's/DOE's purpose in undertaking the resource assessment

- Overview of State Ground Water Protection Efforts. This section places the resource assessment technique in the context of ground water protection efforts

- Administration and Organization of the State's Resource Assessment. This section provides an overview of the resource assessment and of the agencies that participated in the assessment

- Conducting the Resource Evaluation. This section discusses which resource assessment Components and Approaches the State/DOE used. This discussion ties the State's/DOE's efforts back to Components and/or Approaches outlined in this Technical Assistance Document. This section also describes how the State/DOE collected, managed, and synthesized data for the resource assessment and prepared the final product of the assessment

- Decision-Making Based on the Resource Evaluation. This section discusses how information from the resource evaluation was used as part of resource assessment to achieve the most prudent decision-making for ground water protection management by the State/DOE. The discussion focuses on how the information was or is being employed in making land-use decisions and in influencing other policy related decisions

- Other Sources of Information. This section includes the sources of information used in the development of this case study and where additional sources of information on the case study can be located

This appendix includes the following case studies:

- Arizona Department Of Water Resources Hydrologic Map Series
- Potential for Contamination of Shallow Aquifers in Illinois
- Sensitivity Assessment of Major Aquifer Systems of Allen County, Indiana
- Big Sioux Aquifer Assessment in South Dakota
- Hydrologic Assessment of U.S. Department of Energy's Oak Ridge, Tennessee Reservation

The DOE case study on the Oak Ridge Reservation follows a slightly different format than the other case studies. The DOE case study discusses DOE ground water protection requirements, the resource assessment undertaken at Oak Ridge, and DOE cooperative relationships with relevant State agencies.

ARIZONA

Department of Water Resources
Hydrologic Map Series

PURPOSE OF THIS RESOURCE ASSESSMENT:

The Arizona Department of Water Resources (ADWR) hydrologic map series is a cooperative effort with the U.S. Geological Survey to study and evaluate the ground water resources of the State as an essential element in planning, management, and policy development processes.

Overview of State Ground Water Protection Efforts

More than 60 percent of the water resources supplied in Arizona comes from ground water. Most of the ground water supplies, especially in the central and southern sections of the State, are found in unconsolidated alluvial and valley fill deposits between 800 and 1200 feet thick. Depth to water ranges from a few feet to several hundred feet below ground surface.

The semi-arid climate with summer temperatures often exceeding 100°F and low annual precipitation of between 7 and 8 inches can place limits on the adequate availability of surface water in the State. As a result, Arizonans rely heavily on ground water resources for domestic and commercial purposes. The principle uses of water resources are:

- municipal (including domestic drinking water and urban irrigation)
- industrial
- agricultural irrigation

By the year 2025 the percent of consumptive use by category is expected to shift dramatically. Municipal use may more than double while agricultural use may be reduced by half (ADWR, 1991).

Many areas in the State have experienced severe ground water overdrafts. Overdraft conditions exist when ground water extraction exceeds recharge. Ground water withdrawals in central and southern Arizona have exceeded recharge by approximately two million acre-feet per year and have resulted in the lowering of ground water levels by up to 600 feet in some areas. Ground water levels in the Phoenix Active Management Area (AMA) have declined up to 450 feet at certain locations, averaging a decline of 2.7 feet per year between 1923 and 1983 (ADWR, 1991).

The lowering of ground water levels can create three significant problems in addition to the depletion of water resources:

- increased well drilling and pumping costs
- decline in water quality resulting from the use of deeper, more highly mineralized ground water
- earth subsidence resulting in cracks and fissures at the earth's surface

In many areas, these conditions have made it economically unfeasible to extract ground water for some uses (ADWR, 1991).

Arizonans, seeking to address the growing problems associated with ground water overdrafts, and recognizing the necessity of wise planning and management of water resources, joined in a comprehensive effort to formulate a resource protection plan. Those involved included State and local leaders and legislators, private commercial interests such as industrial and development concerns, special interest groups, and the general public. The result was Arizona's Groundwater Management Code (Code) enacted in 1980. The Code has three important goals:

- control severe overdraft
- provide a means to allocate the limited ground water resources
- augment ground water usage through water supply development

In addition, the Code created the ADWR and charged it with the responsibility to administer the Code's provisions.

A key provision of the Code was to target regulations to areas of the State with the most severe ground water problems. To accomplish this, the Code established three levels of water management. The most regulated level is the Active Management Area which includes 80 percent of the State's population and 70 percent of ground water overdrafts. The second management level is the Irrigation Non-expansion Area (INA) where, depending on when ground water was first used for irrigation, limitations are imposed on additional ground water withdrawn for agricultural purposes. The lowest level of regulation includes provisions that apply Statewide where ground water concerns are less critical. To assist management efforts further, ground water resources are organized geographically by ground water basins and sub-basins rather than geopolitical boundaries.

Recognizing that ground water resources must be of suitable quality as well as of sufficient quantity for intended uses, the legislature enacted the Environmental Quality Act (EQA) of 1986. The

EQA created the Arizona Department of Environmental Quality (ADEQ), effective July, 1987, "to administer State programs for water quality, air quality, solid waste, and hazardous waste" (ADWR, 1991). Because ground water quantity and quality are interrelated issues, both the ADWR and ADEQ have authority to regulate ground water quality and the two agencies coordinate efforts to achieve ground water resource protection goals.

In the Phoenix AMA, the goal of the Ground Water Quality Management Program, which is principally administered by ADWR, is to control ground water quality and maximize the quantity available for beneficial use. To meet this goal, four objectives are recognized by ADWR:

(1) protect ground water quality from degradation
(2) collect ground water quality data on a regular basis
(3) identify those areas with ground water of poor quality
(4) correct problems

Although both ADWR and ADEQ are responsible for studying and characterizing the State's ground water resources, ADWR assumes much of the data compilation activities with technical support provided by ADEQ.

Administration and Organization of the State's Resource Assessment

A characterization of the State's ground water resource is the initial step in, and becomes the basic tool to achieve ground water quantity and quality goals. ADWR has been gradually assuming ground water resource characterization responsibilities from the U.S. Geological Survey (USGS) which has been conducting characterizations for many years. Ground water resource characterization remains a cooperative effort among the USGS, ADWR, and ADEQ, however. Collected information and data bases are shared between the three agencies with lead responsibility resting with ADWR.

A Memorandum Of Understanding (MOU) has been developed between ADWR and ADEQ specifically stating the roles of each agency including responsibilities, staff and financial resource allocation, and coordination of activities. Although the current MOU expired in June, 1992, a verbal agreement between the two agencies continues the MOU virtually unchanged.

The product of the joint agreement and the agencies' collaborative efforts is the Hydrologic Map Series. These maps were produced to incorporate ground water quality concerns into management programs. The subject of this case study is Hydrologic Map Series Report Number 12, Maps Showing Groundwater Conditions in the West Salt River, East Salt River, Lake Pleasant, Carefree and Fountain Hills Sub-Basins of the Phoenix Active Management Area, Maricopa, Pinal, and Yavapai Counties, Arizona--1983 (Report Number 12) (Reeter and Remick, 1986). The report typifies ground water resource evaluations conducted in Arizona.

Report Number 12 combines data compiled from multiple sources by ADWR hydrogeologists. Specifically, the principle sources of data are:

- USGS's WATSTORE data base
- EPA's STORET (Storage and Retrieval) data base containing data collected by ADEQ and other local, State, and Federal agencies
- ADWR's GWSI (Ground Water Site Information) system
- consultant reports

The information in the data bases was compared to and used to fill data gaps and update and confirm other published reports. Data on certain water quality parameters such as volatile organic compounds were provided by ADEQ.

Conducting the Resource Evaluation

The goal of the assessment program is to provide the information necessary to combine ground water quality and quantity concerns into ADWR management programs. Hydrologic Map Series Report Number 12 includes three maps, each presenting data essential to meeting the goal.

Map number one presents depth to water and the elevation of the water table. Water level contours with a contour interval of 50 feet are included as are the locations of known water wells and springs. The location and extent of valley fill deposits and bedrock are presented. Accompanying text describes the hydrogeologic conditions of the area. Background information on the legislative and organizational structure and a synopsis of the existing ground water problems are also provided.

Map number two presents changes in ground water levels between 1976 and 1983. Water levels were measured in selected wells; declines and increases are notated by a "-" or "+" respectively, with the corresponding value. Hydrographs for selected wells are included showing water level fluctuations measured from ground surface for the years between 1945 and 1985. A table containing ground water pumpage in acre-feet per year from 1915 to 1983 completes the data presented on map two.

Map number three presents the chemical quality of water in the management area. Numerical data from selected wells indicate dissolved solids and fluoride concentrations in the ground water. In addition, diagrams showing cation/anion concentrations for major constituents (i.e., sodium, chloride, calcium, bicarbonate, magnesium, and sulfate) are given for selected wells. The diagrams provide "a means of comparing, correlating, and characterizing similar or dissimilar types of water" (Reeter and Remick, 1986).

Each of the maps presents certain information in common with the others. The information presented is:

- boundaries of the study area
- Public Land System grid (Township and Range)
- prominent natural surface features (e.g., surface water and mountain ranges)
- urban areas
- the location and extent of valley fill deposits and bedrock

The combination of data presented in the maps along with accompanying text, provide a very useful means of evaluating the ground water resources in detail fine enough for overall planning and management purposes. The data components are relatively congruent with the following Technical Assistance Document Components:

- Aquifer and Aquifer System Occurrence (Component #2)
- Water Table and Potentiometric Surface (Component #3)
- Hydraulic Properties (Component #4)
- Chemical and Physical Characteristics of Aquifers and Overlying Materials (Component #9)
- Ambient Ground Water Quality (Component #10)

However, not every Component is necessarily applicable or utilized. For example, a detailed description of lithology is not included because the alluvial deposits, which contain the majority of ground water resources, are fairly homogeneous throughout the area and need be described only once in text format. Likewise, the movement and flow of ground water is relatively consistent and can be determined by changes in the water table elevation above the datum (mean sea level).

As previously mentioned, the data presented on the maps were compiled from a variety of sources utilizing the data bases and technical expertise of local, State, and Federal agencies. In addition, the data collection process is an ongoing cooperative effort. As new information becomes available, it is input to the appropriate data base. ADWR and ADEQ monitor thousands of wells annually and attempt to update the information in targeted areas (areas in greatest need) every three years. Maps are updated as needed as sufficient new data become available.

Decision-Making Based on the Resource Evaluation

The hydrologic map series is intended and designed to assist ADWR and ADEQ in their respective missions to manage ground water quantity and quality. In so doing, the maps are used to identify areas potentially requiring special well construction methods or spacing. This helps protect ground water from degradation. To assist ADWR with long-range ground water requirement planning, the maps can be compared with land use, urban growth projection, wildlife, and other similar types of maps. In areas identified as having ground water unsuitable for drinking water, other water supplies can be utilized instead, thus protecting the public health. Where public supply wells produce water unsuitable for drinking purposes, the type and level of contaminants can be addressed with appropriate treatment technologies.

Water quantity planning decisions also rely on accurate and current supply information. In areas where ground water overdrafts occur, or where supplies are insufficient to meet projected demand, ground water pumping can be reduced and future well development minimized by placing limits on extraction and restricting the number of permits issued. Additional programs such as incentives to conserve existing supplies; reduce demand, encourage reuse, and to secure new supplies or augment current supplies could also be implemented. If necessary, residential and industrial development plans can be required to directly address and mitigate adverse conditions affecting ground water quantity and quality before being approved to allow development.

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ILLINOIS

Potential for Contamination of Shallow Aquifers in Illinois

PURPOSE OF THIS RESOURCE ASSESSMENT:

The purpose of this study was to describe and map geologic materials to a depth of 50 feet throughout the State. Such an understanding and representation of geologic materials allowed the ISGS and others to determine the potential sensitivity of underlying aquifers to contamination.

Overview of State Ground Water Protection Efforts

Approximately 80 percent of the people residing in the State of Illinois, excluding the Chicago metropolitan area, depend upon ground water for their drinking water. In addition to household uses, the ground water resource serves industry, business, and agriculture in the State. Ground water also contributes a large portion to the surface water flows in Illinois through discharge to streams. The ground water input contributes to many surface water uses and is important in maintaining surface water flow, especially during low to normal precipitation periods.

Ground water used for public water supplies in Illinois is usually obtained from high-yielding wells in unconsolidated glacial drift materials or from consolidated rock formations that may underlie the drift deposits. These shallow water-bearing bedrock aquifers are limestone or dolomite and the deeper aquifers are sandstone. The potential for ground water resources to become contaminated is a critical concern in Illinois, particularly for the shallow aquifers occurring throughout the State.

Understanding the importance of the ground water resource and the potential for its contamination from diverse sources, the Illinois Legislature and Governor enacted the Illinois Groundwater Protection Act (IGPA) in 1987. The Act seeks to "restore, protect and enhance the ground water ... as a natural and public resource." It also establishes a unified ground water protection program including ground water protection policy, cooperation across State agencies, water well protection zones, resource mapping and assessment, recharge area protection, and ground water quality standards.

The IGPA created the Interagency Coordinating Committee on Groundwater (ICCG) to direct efforts of State agencies and facilitate implementation of the IGPA. Ten State agencies participate in the ICCG. The Illinois Environmental Protection Agency (IEPA) and the Department of Energy and Natural Resources (ENR) are very active in the implementation of the Act. ENR is responsible for developing a comprehensive ground water evaluation program, including resource assessments, data collection and automation, and ground water monitoring. The Illinois State Geological Survey (ISGS) and Illinois State Water Survey (ISWS), divisions of ENR, developed a long-term ground water evaluation plan, which is being implemented as funds become available.

Administration and Organization of the State's Resource Assessment

The Illinois State Geological Survey has been studying the State's ground water resources for over fifty years. During that time, the ISGS has published numerous ground water resource evaluations at both the county and State level and has provided valuable information to the IEPA and ENR on the hydrogeologic characteristics of the State's ground water resources. The Illinois State Water Survey has been conducting ground water studies even longer. The agency performs aquifer tests across Illinois and maintains an extensive data base on aquifer properties. The ISWS was organized specifically as the State's water resource research agency and primarily deals with water quantity and quality issues.

Ground water evaluations conducted in Illinois provide the foundation for a number of activities. For instance, the ISGS has studied areas sensitive to landfilling of wastes and the potential for contamination of unconsolidated and bedrock aquifers. The ISGS has mapped and demonstrated the potential for contamination of aquifers at both the State and county level. These studies and others continue to provide important hydrogeologic information for environmental decision making. Of particular note is the ISGS Statewide study on the Potential for Contamination of Shallow Aquifers in Illinois, completed in 1984. The purpose of this study, initiated and supported by the IEPA, was to describe and map geologic materials to a depth of 50 feet throughout the State. Such an understanding and representation of geologic materials allowed the ISGS and others to determine the potential vulnerability of underlying aquifers to contamination. This mapping increased awareness regarding the contamination potential of Illinois' shallow aquifers by showing that about 50 percent of the State was characterized as having an aquifer within 50 feet of the surface. The study was a key element for promoting ground water protection legislation in the State.

As part of the study, the ISGS produced maps of the entire State at a scale of 1:500,000 that are unique in their detail of geologic information. The maps' intended uses are to:

- suggest areas, not specific sites, where disposal of wastes will have the minimum potential for contaminating ground water resources

- screen areas with low contamination potential, as part of the process of locating new disposal sites

The Potential for Contamination of Shallow Aquifers in Illinois study relied almost entirely on geological and hydrogeological information already compiled by the ISGS and ISWS. The study coordinated and synthesized information collected as part of other county and State level studies. In addition, thousands of water well logs were evaluated for purposes of identifying potential aquifer materials. This approach demonstrates how existing data often form a base of information that can be used in future resource assessments. This approach also avoids duplication of effort in collecting baseline geologic and hydrogeologic data and information.

Conducting the Resource Evaluation

The Potential for Contamination of Shallow Aquifers in Illinois study describes and maps geologic materials on the basis of thickness, texture, permeability, and stratigraphic position. Since waste effluent travels through different materials at different rates, the contamination potential of aquifers depends on the protection afforded by overlying and underlying less permeable materials. As a result, the combination of hydrogeologic properties and stratigraphic position of geologic materials provides the basis for mapping the potential for the contamination of aquifers. The general premise of the mapping exercise is that the deeper the aquifer, and the thicker and finer-grained the overlying confining materials, the lower the potential that the aquifer will become contaminated. A rating scheme that addresses the potential for contamination allows officials to compare sequences of geologic materials in any area of the State.

The ISGS was interested in collecting and synthesizing the following information to determine the potential for contamination of shallow aquifers:

- distribution of geologic materials (see Component #1)
    - Bedrock
    - Glacial and other surficial deposits

- source, movement, and availability of ground water
    - Location and areal distribution of aquifers (see Component #2)
    - Hydraulic properties and aquifer materials (see Component #4)
    - Aquifer confinement and interconnections (see Component #5)
    - Recharge characterization (see Component #6)

- physical properties that reduce concentration of contamination (see Component #9)
  - Dilution, dispersion, and filtering
  - Attenuation

An understanding of the distribution of geologic materials in Illinois allows the ISGS to assess the potential movement of contaminants through vertical sequences of different geologic materials. Knowledge of the source, movement, and availability of ground water provides important information on the location of aquifers, the movement and flow of water within aquifers, and the potential movement of contaminants into and within aquifers. An understanding of the contaminants and the physical properties that reduce concentrations of contamination provides further insight into how contaminants move through geologic settings and aquifers.

Through a detailed search of previously conducted ISGS and ISWS studies and maps, as well as an evaluation of water well logs on file, the ISGS pieced together a 20-foot and a 50-foot depth geologic stack-unit map (Berg and Kempton, 1988) to demonstrate how geologic materials are distributed both horizontally and vertically throughout Illinois. A stack-unit map shows the areal distribution of geologic materials over a specified area in their order of occurrence to a specified depth. Sources of information used to construct these stack-unit maps included:

- general ISGS publications and maps such as the *Geologic Map of Illinois* and *Quaternary Deposits of Illinois*
- other ISGS studies including subsurface stratigraphic data from maps, field notes, test drilling, and water well logs
- evaluation of more than 25,000 well logs and sample-set descriptions

From this work, the ISGS developed two contamination potential maps. The map for land burial of municipal waste, with a depth limit of 50 feet, was constructed first. Then the map for surface and near surface disposal of wastes, with a depth limit of 20 feet, was made by transferring some unit boundaries from the land-burial map.

Within map boundaries for both maps, related stack units or vertical sequences of materials were combined into sets of geologic sequences. Unique sets were identified and then described by relating type, texture, and permeability of materials to depth, thickness, and the position in the geologic sequence. These sets of vertical geologic sequences were then rated by comparing the capacities of earth materials to accept, transmit, restrict, or remove potential contaminants from waste effluent. Finally, assigned ratings were added to each specific map unit. The two maps show the distribution of sequences of geologic materials and their comparative ratings. Resulting products are aquifer sensitivity maps (see Approach #1).

The ISGS faced a number of difficulties in preparing the stack-unit maps for the entire State (Berg and Kempton, 1988). In general, the availability and accuracy of data decreases as depth increases. Many of the maps used in this study relied on a variety of different scales. Because the final map product was at a scale of 1:500,000, some detail on smaller units was lost. Also units less than three feet thick were too small to be included unless they were continuous over a relatively large area (i.e., three to four square miles).

Decision-Making Based on the Resource Evaluation

The map for land burial of municipal wastes and the map for surface and near surface disposal of wastes provide a sound basis for preliminary appraisals of earth materials and geological sequences on a regional scale for:

- selecting new waste disposal sites
- assessing the suitability of existing waste disposal sites and operations by relating their location to the rating indicators on the maps

The maps can also be used to show the generalized geology of the State of Illinois to a depth of 50 feet and can be used in evaluation projects to describe and rate sequences of geologic units for sand and gravel resources, shallow drinking water supplies, and general construction conditions.

The Potential for Contamination of Shallow Aquifers in Illinois study maps have been used widely by local and county authorities to support zoning and siting decisions. IEPA has applied the maps to assist in the selection process for new waste management facilities and to gauge the potential for contamination from existing facilities.

These maps, with the addition of deeper aquifer information and contamination source data, also allowed IEPA, with the assistance of the ICCG, to select Ground Water Protection Planning Regions. These Regions consist of multi-county areas initially chosen because of their high potential vulnerability to ground water contamination.

In addition, the ISGS maps from this study, along with deeper aquifer information, were used by the Illinois Department of Nuclear Safety to screen the State for a low-level radioactive waste disposal site.

The ISGS maps have two limitations as waste management decision-making tools. First, these maps cannot be used to evaluate sites for wastes that require long periods of containment, such as high-level radioactive wastes. Second, these maps can only be used to assess the regional appropriateness for waste management activities, and cannot be used as substitutes for site-specific evaluations because of local complexities in geologic materials. A number of site-specific factors and seasonal factors must be considered in determining an appropriate site for waste management activities. Many of these factors were beyond the scope of this project and the scale of these maps.

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Natural Resources Building
615 East Peabody Drive
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(217) 244-2776

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INDIANA

Sensitivity Assessment of Major Aquifer Systems of Allen County

PURPOSE OF THIS RESOURCE ASSESSMENT:

The purpose of this study was to identify the distribution of major aquifer systems and their sensitivity to contamination in Allen County, Indiana.

Overview of State Ground Water Protection Efforts

Indiana depends on its ground water resource for a number of beneficial uses. Nearly 60 percent of the State's five million residents use ground water for drinking water purposes. Ground water is also vital for Indiana's industrial and agricultural growth and development. Ground water consumption and use in Indiana is expected to increase in the foreseeable future.

The availability and quality of ground water varies widely across Indiana. Indiana relies on bedrock aquifers in the southwest and glacial outwash aquifers beneath and adjacent to major rivers and tributaries for ground water. Most fresh or potable ground water in Indiana occurs at depths of 40 feet to 300 feet. Highly mineralized waters are usually found at greater depths. Much of Indiana's ground water is moderately to excessively hard as a result of the presence of dissolved calcium, and it locally contains high levels of iron, manganese, or hydrogen sulfide. Conventional water treatment can correct these problems for normal uses.

Even though there is an abundance of high quality ground water to provide for the State's needs, Indiana recognizes that its continued economic growth and quality of life will depend on the actions taken to maintain this vital resource. Indiana's ground water protection policy requires that existing and potential beneficial uses of ground water be protected. The policy allows for limited degradation of some ground waters, if beneficial uses are not affected and the degradation is judged to be economically or socially justifiable. The policy, however, also prohibits degradation of ground water whose quality exceeds existing standards (Indiana Administrative Code, Title 330, 1987).

The responsibilities of implementing Indiana's ground water protection policy falls on three separate State agencies. The Indiana Department of Environmental Management (IDEM) administers applicable State and Federal laws through regulatory programs to protect the quality of ground water from potential pollution sources. The Indiana Department of Natural Resources (IDNR) is responsible for management of oil, gas, and mining activities, water well drilling, ground water information, and aspects of water quality. Within the IDNR, the Division of Water and Indiana Geological Survey provide valuable information on ground water resources to the other State agencies. Finally, the State Board of Health administers septic system regulations and ensures that public water supplies provide safe drinking water. Indiana's Inter-Agency Ground Water Task Force coordinates the implementation of ground water protection activities across the three agencies.

Administration and Organization of the State's Resource Assessment

Indiana recognizes that one of the most important features of a ground water protection program is the development of detailed maps and descriptions of the State's major aquifer systems. As part of its Ground Water Protection Strategy, Indiana identified the following ground water resource assessment needs:

- delineation of the lateral distribution and thickness of aquifers
- identification and delineation of aquifer recharge and discharge areas
- information on ground water flow rates and direction
- data on the physical properties of aquifers and confining units, such as permeability, porosity, and grain size

The IDNR's Division of Water and the Indiana Geological Survey have gathered and synthesized much information on Indiana's ground water resources. As part of the State's ground water resource assessment efforts, IDNR has initiated a phased regional study approach. These regional studies use river basins as boundaries and map aquifer environments, computerize well records, and collect water quality data for each basin. Through this approach, IDNR is seeking to delineate and name aquifer systems in a standard fashion.

In addition to assisting the State in conducting a comprehensive assessment of its ground water resources, the Indiana Geological Survey (IGS) conducts ground water resource assessments for individual counties. An example of such an assessment is a study to identify the distribution of major aquifer systems and their sensitivity to contamination in Allen County. At the request of Allen County, IGS conducted a study that resulted in the preparation of 90 open-file maps at a scale of 1:24,000 showing hydrogeologic settings and their sensitivity to contamination, and a county report that describes the bedrock geology, glacial geology, hydrogeological framework, general ground water availability, and sensitivity of aquifers to pollution. The county report will be accompanied by nine maps of the entire county, each at a scale of 1:63,360. These county maps will include:

- distribution and types of data points
- bedrock geology and topography
- total thickness and sequence characteristics of unconsolidated materials
- geology and topography of the buried surface of the late Wisconsin Trafalgar megasequence
- stratigraphy and distribution of aquifers and aquifer systems
- near surface geologic sequences and thickness of surface till between the land surface and mapped aquifers
- potentiometric surface of the bedrock aquifer system, including recharge and discharge areas
- potentiometric surface of shallow sand and gravel aquifer systems, including recharge and discharge areas
- sensitivity to contamination of mapped aquifers

The report and accompanying maps are expected to be published by Allen County by mid-1994.

Conducting the Resource Evaluation

Allen County is located in northeastern Indiana and is situated between three different geologic-physiographic regions. Within the county, limestone, dolomite, and shale bedrock are overlain by glacial deposits that range in thickness from less than 30 feet in the east to more than 340 feet in the northwest. The bedrock and the unconsolidated deposits contain three aquifer systems that supply the majority of water for most ground water uses in the county. Allen County's interest in protecting its ground water resources led county officials to request and fund IGS to study the distribution of major aquifer systems and their sensitivity to contamination.

IGS compiled the county report and maps from sets of detailed hydrogeologic and stratigraphic maps constructed on USGS 7.5-minute topographic quadrangles. Each set of maps for each of Allen County's twenty quadrangles includes:

- distribution and types of data points
- bedrock topography and geology (see Component #1)
- stratigraphy of aquifer systems and confining units (see Components #2 and #5)
- near surface geologic sequences and thickness of till confining units (see Component #2 and #5)

- potentiometric surfaces of major aquifer systems, showing recharge and discharge areas and the locations and approximate zones of influence of registered high capacity wells (see Components #3 and #6)
- sensitivity of ground water to contamination (see Approaches #1 and #3)

IGS employed a variety of new and existing information to develop these maps, including:

- 6,400 water well and test boring records
- 200 down-hole gamma-ray logs
- 75 down-hole sample sets
- samples collected from 15 surface exposures
- 340 seismic shots
- soil maps developed by the Soil Conservation Service
- geomorphic relationships

The maps were derived from the above data through a number of methods. For example, cross-sections and fence diagrams representing more than 1,350 linear miles were constructed and utilized to interpret the depositional environments, facies relations, and three-dimensional geometry of aquifers and confining units. Stratigraphic correlations of these units was based chiefly upon their physical properties, including textural, mineralogical, geotechnical, and down-hole geophysical characteristics. The identification of aquifer systems was made on the basis of both stratigraphic relationships as well as hydrodynamic considerations, such as analysis of physical and hydrogeochemical characteristics of till confining units, detailed contouring of potentiometric surfaces based on stratigraphic position, and recognition of distinct flow regimes in adjacent or subjacent geologic units.

Due to the irregular distribution and variable quality of data points, the maps are not suitable for detailed site-specific evaluations. The maps are intended for comparative purposes such as site screening and general planning activities. These maps, however, are unique, because they show the distribution of different kinds of data points. An understanding of the distribution of data points allows the user to make a direct inference regarding the reliability of the maps for any region or point of interest. For example, there are specific sites that may have as many as 50-75 high-quality data points, all within an area as small as one square mile. On the other hand, areas of similar size elsewhere in the county may contain few or no data points, meaning that hydrogeologic relationships were inferred from nearby areas within the same hydrogeologic settings that have more data. While the maps are not a substitute for site-specific investigation, the maps provide an extremely useful local and regional perspective for such investigations.

The ground water sensitivity maps indicate the relative potential for contamination of a particular aquifer system as it varies across the landscape. The sensitivity maps are very generalized because of the wide variety of contaminants and the variety of pathways into the ground water. IGS developed a numerical index to evaluate ground water sensitivity. This approach allows:

- a direct comparison among differing geologic regions
- an interpretation of the relative sensitivities of the many areas that fall into intermediate sensitivity classes

IGS used four basic factors to formulate the sensitivity index:

- the type and hydraulic conductivity (relative) of aquifer media
- the type and thickness of material overlying the aquifer and the degree of confinement of the aquifer
- the position within the ground water flow system (i.e., recharge and discharge areas)
- the characteristics of the surface soil

These factors directly influence the rate at which a potential contaminant can migrate into an aquifer, the potential for attenuation of the contaminant, the fate of the contaminant once it reaches an aquifer, and the potential impact on overall water quality within the aquifer system. The sensitivity index also contains three key components for each of the four factors listed above:

- weights
- ranges
- ratings

The sensitivity index for each map unit was determined by summing the products of the weight and rating for each factor. It must be emphasized that individual index numbers have no absolute meaning in and of themselves. The index numbers are not indicators of absolute contamination potential, and should only be interpreted relative to one another.

Decision-Making Based on the Resource Evaluation

The ground water sensitivity maps for Allen county provide a sound basis for preliminary appraisals of earth materials and geological sequences on a county scale and for a generalized understanding of the potential for contamination of the County's aquifer systems. These quadrangle maps can be particularly useful for:

- zoning decisions to limit the potential adverse impacts to ground water
- screening of potential sites for hazardous and solid waste disposal facilities
- prioritization of aquifers and geographic areas for protection

The maps and reports have other uses including showing the generalized glacial geology and hydrogeology of Allen County, as well as wellhead protection areas, foundation conditions, mineral resources, and generalized ground water availability.

In Allen County, the Department of Planning Services, the Office of Environmental Management, and the Fort Wayne/Allen County Board of Health use the maps as a basis for management decisions. The Department of Planning Services uses the maps to:

- evaluate land-use proposals from the Planning Commission and the Board of Zoning Appeals
- establish urban service areas as part of a long-term comprehensive planning strategy for Allen County (Service areas are those parts of Allen County where development of many types is encouraged)
- review appropriateness of speculative siting proposals for industrial parks and commercial areas

Specifically, the county report and maps have been used to protect ground water recharge areas in the Huntertown Urban Service Area. The maps identified the regional importance of the ground water recharge area in Huntertown. As a result, the areal extent of the Huntertown Urban Service Area was reduced to ensure the protection of the recharge area from development.

The Allen County ground water resource assessment maps are very useful as a comparative tool for screening sites for solid and hazardous waste facilities, industrial development, and related activities, because the maps indicate the range of geologic variability that can be expected within each map unit as well as between map units. However, these maps have some limitations as decision-making tools. These maps cannot be used for site-specific evaluations because of local complexities in geologic materials. These maps can only be used to assess the regional appropriateness for certain activities. A number of site-specific factors and seasonal factors must be considered in determining appropriate uses for specific sites. Many of these factors were beyond the scope of this project and the scale of these maps and must be completed on a case-by-case basis.

Other Sources of Information

State Contact:	Tony Fleming Indiana Geological Survey 611 N. Walnut Grove Bloomington, Indiana, 47405 (812) 855-7428	Local Contact:	Dennis Gordon, Director Allen County Department of Planning Services 630 City-County Building One Main Street Fort Wayne, IN 46802-1804 (219) 428-7607

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SOUTH DAKOTA

Big Sioux Aquifer Assessment

Overview of State Ground Water Protection Efforts

South Dakota is largely dependent on its ground water for water supply. Approximately 66 percent of the 674 million gallons of water used per day in South Dakota is taken from the ground. The uses of ground water include domestic purposes, livestock watering, irrigation, and industrial use. The majority of the State's public water supplies rely on ground water, and virtually everyone not supplied by public water systems is dependent on ground water from private wells.

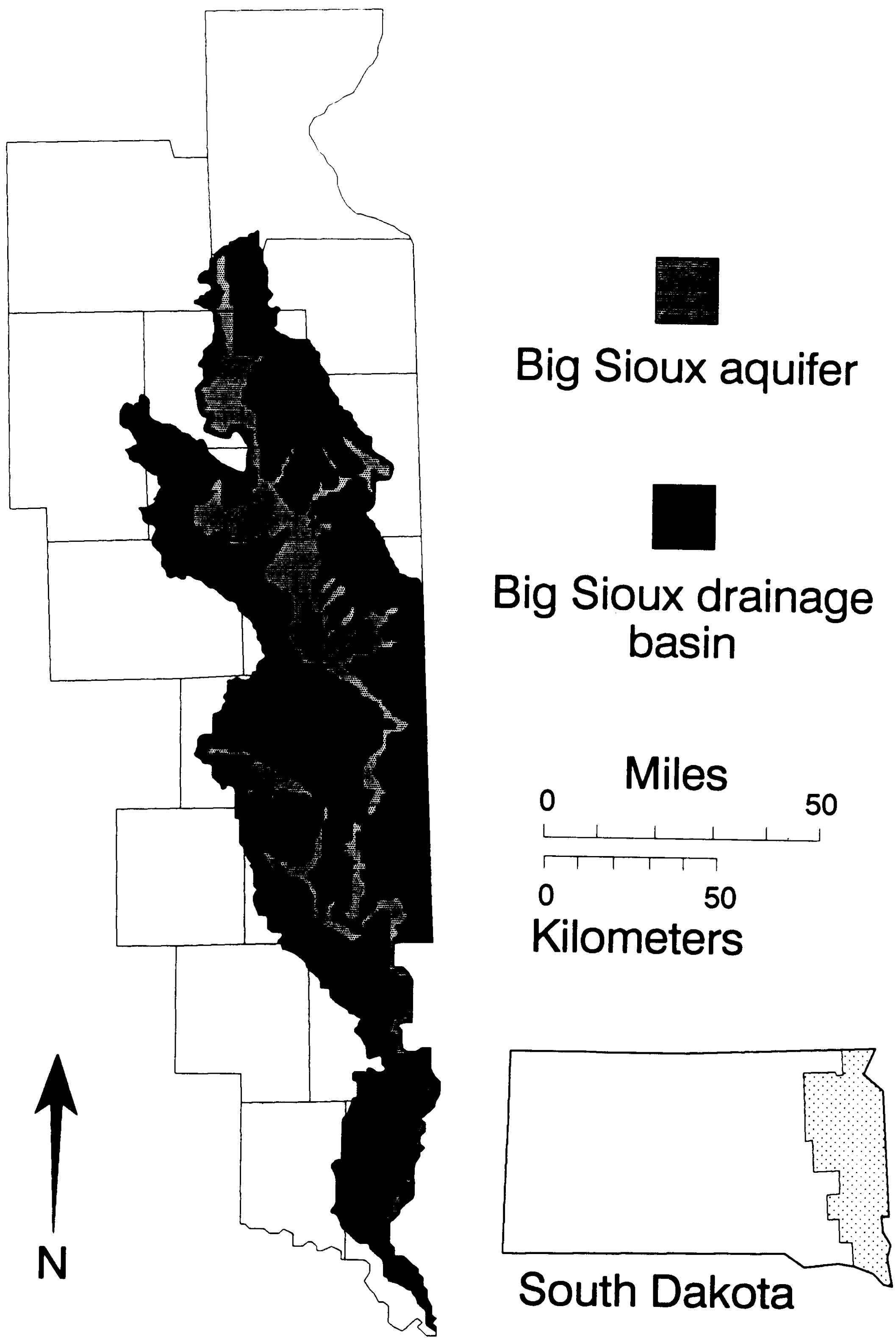
> **PURPOSE OF THIS RESOURCE ASSESSMENT:**
>
> The original intent of the ground water resource assessment of the Big Sioux aquifer (Fig. B-1) was to delineate the areal extent, thickness, and water quality for use in making water development decisions for domestic, municipal, and irrigation purposes. However, because of increasing demands for water and realization of the vulnerability of this aquifer to contamination, the hydrogeologic data are now extensively used for water management, including various ground water protection activities.

The Big Sioux aquifer of glacial origin is the most utilized source of ground water for drinking water purposes in South Dakota and serves approximately one-third of the State's population (see Figure B-1). Additional major sources of ground water for South Dakota's population are the other glacial aquifers in the eastern half of the State and alluvial and bedrock aquifers throughout the State. Surficial aquifers and the bedrock aquifers that outcrop in areas of the Black Hills are vulnerable to contamination. The three most significant categories of potential ground water contamination are:

- contamination from petroleum, fertilizer, pesticides, and other chemicals from releases due to equipment failure and mishandling
- contamination of domestic wells due to poor well construction and the well's location relative to point sources of pollution, such as septic systems, barn yards, feed lots, and lagoons
- contamination from non-point sources of pollution

Recognizing the immeasurable value of ground water, the Governor-sponsored Centennial Environmental Protection Act of 1989 was passed by the South Dakota Legislature. This act establishes the State's ground water goal to "conserve and protect the ground water of the State and

Figure B-1
Big Sioux Aquifer and Drainage Basin



to protect, maintain and improve the quality thereof for present and future beneficial uses through the prevention of pollution, correction of ground water pollution problems and close control of limited degradation parameters permitted for necessary economic or social development." [South Dakota Codified Law 34A-2-104]

The South Dakota Department of Environment and Natural Resources (DENR) has the responsibility for evaluation, appropriation, and development of guidelines for protection of the State's water. The Division of Water Rights deals with the appropriation of water. The Division of Water Resources Management deals with the funding of water projects. The Ground Water Quality Program in the Division of Environmental Regulation, coordinates most of the programs, activities, and funds relating to ground-water protection. The South Dakota Geological Survey (SDGS), a nonregulatory division of DENR, is charged with conducting scientific research for use in developing the State's natural resources and protection of the environment. Hydrogeologic studies and research at the SDGS are varied and serve as a sound basis for the State's ground water protection activities. DENR developed a comprehensive ground water protection strategy in 1987 which is updated each year. This strategy establishes a ground water prioritization process based on the potential for contamination and the impacts contamination would have on aquifers or specific portions of aquifers. According to the strategy, the following criteria are used to prioritize DENR's protection and planning activities:

- areas that will affect public health
- wellhead protection areas/public water supplies
- private water supplies
- ambient water quality with Total Dissolved Solids (TDS) value of 10,000 mg/L or less giving it the beneficial use of drinking water
- vulnerability of the aquifer
- documented water quality problems
- special considerations

Based on these criteria, the Big Sioux aquifer has the highest priority rating.

The State's wellhead protection program has been approved by the U.S. Environmental Protection Agency (EPA). However, prior to approval of the State's plan, significant wellhead protection measures were implemented for a large portion of the Big Sioux aquifer in eastern South Dakota. These protection measures were formulated and implemented under the auspices of city, county, and water-development district authorities working with DENR.

Administration and Organization of the State's Resource Assessment

As part of natural resource assessments, the SDGS and other Federal, State, and local-government entities conduct a variety of ground water related studies, including ground water resource assessments. The SDGS's resource assessment program covers the entire State, and nearly all of the ground water resources of eastern South Dakota have been characterized. The process of resource assessment is not new to South Dakota. The SDGS has been locating, mapping, and evaluating water resources of the State for approximately 100 years. Also, the Division of Water Rights, has been assessing ground water availability for purposes of water appropriation for 37 years. Current resource assessment efforts are merely a continuation of standard practices which have, over the years, resulted in a large data base of hydrogeologic information for many aquifers in the State. Data gathering techniques typically include:

- mapping of surface and subsurface geology
- extensive drilling of test holes
- geophysical logging
- installation of monitoring wells
- monitoring of water levels and water quality
- conducting well inventories
- performance of aquifer tests

Some studies have focused on entire counties or regions while others have concentrated on only a few square miles. As a result of these investigations, numerous reports and maps have been produced. The SDGS maintains a computerized data base containing approximately 32,000 lithologic logs, 3,400 water-quality analyses, and 197,000 water levels. The U.S. Geological Survey (USGS) and the EPA data bases contain additional ground water data.

Conducting the Resource Evaluation

The SDGS and other government agencies have been examining the Big Sioux aquifer in eastern South Dakota for many decades. Studies have shown that the Big Sioux aquifer is a surficial, glacial outwash unit that covers about 770 square miles and is hydraulically connected to the Big Sioux River. Knowledge of the Big Sioux aquifer is primarily based on:

- systematic reconnaissance investigations of the geologic and hydrologic resources of most counties in eastern South Dakota

- a study, conducted jointly by SDGS and USGS, that focused specifically on the entire extent of the Big Sioux aquifer
- studies by SDGS to locate water sources or improve water quality for cities and rural water systems
- systematic gathering of data on nitrates and pesticides over the areal extent of the aquifer through a permanent network of monitoring wells
- research to better quantify surface and ground water interaction between the Big Sioux River and the Big Sioux aquifer

Funding of investigations of the Big Sioux aquifer has been through the South Dakota DENR, including SDGS, as well as through the East Dakota Water Development District, individual communities, rural water systems, counties, USGS, EPA, and the South Dakota Department of Agriculture. Different projects have utilized various combinations of these funding sources but State and local funds have been involved in every project. Work on these investigations has been performed by the SDGS and USGS, although USGS has usually participated only in large areal assessments. Field activities related to these studies have taken from a few weeks to several years to complete and have utilized one or two geologists and hydrologists per project and drilling and well-installation crews ranging in size from three to six people.

An extensive data base is available for the Big Sioux aquifer and includes records for 5,667 test holes and 2,187 wells. In addition, the State has 656 monitoring wells in the Big Sioux aquifer. These data and water level and water quality records are maintained in a computerized data system (see Components #3, #8, and #10). Numerous aquifer tests have also been performed. This data base plus the numerous ground water studies provide the basis for an overall resource assessment of the aquifer.

Mapping of surface and subsurface geology has defined the regional geologic setting and allowed delineation of three-dimensional spatial relationships of all sediments (see Component #1). The Big Sioux aquifer occurs at or near land surface, is highly permeable, and occurs primarily under unconfined conditions. Thus, the entire aquifer is extremely susceptible to contamination. Good regional characterization of ground water flow directions allows an understanding of recharge and discharge areas.

Data indicate that throughout much of its course, the Big Sioux River and the Big Sioux aquifer have extensive interaction. In fact, pumping in the Sioux Falls well field has caused cessation of flow in certain portions of the Big Sioux River (see Component #7). Hydrologic testing and computer modeling have refined this relationship in certain areas. These studies have also identified recharge-discharge relationships, determined potential yield, and ground water time of travel (see Component #6).

There are currently 1,030 water-quality analyses in SDGS's computerized data base for the Big Sioux aquifer. Additional analyses are available from public water suppliers. The majority of available water quality data deals only with general inorganic parameters, however, limited information is also available on pesticides and volatile organic compounds. The information base on pesticides and volatile organic compounds is growing as wellhead protection efforts proceed and as research continues on the quality of water in the aquifer.

Each investigation conducted by the SDGS or the USGS is accompanied by a report of findings which typically includes tabular data, information on water quality, and map presentations of data and interpretations, which include the areal extent and thickness of the aquifer, water table contours, and ground water flow directions. These reports are available from the respective organizations. The DENR is developing a Geographic Information System (GIS) which will include all pertinent hydrogeologic data. The use of a GIS will enhance decision making regarding aquifer issues and should allow for more rapid and widespread use of aquifer-related information.

Decision-Making Based on the Resource Evaluation

While most of the work done on the Big Sioux aquifer relates only to the first part of EPA's definition for a resource assessment (i.e., a classical, scientific resource evaluation), some of the hydrogeologic study results regarding this aquifer are being used by planners and water managers for a number of purposes, including:

- the appropriation of water rights
- management of water use for municipal, industrial, and irrigation purposes
- prioritization of public water supplies for wellhead protection
- the delineation of wellhead protection areas
- vulnerability assessment of public water supplies to determine monitoring frequency

Existing aquifer maps and other hydrogeologic information, such as data on the hydraulic properties of the aquifer, are regularly used by the Division of Water Rights, to estimate the potential impact of one water right upon another as part of the decision-making process regarding the appropriation of water rights. Any large-scale development of the aquifer is directly dependent upon the granting of water rights. Also, the hydrogeologic information is used by the city of Sioux Falls (population 105,000) to manage the pumping of water from its well field and was the basis for the development of contingency plans to deal with a major contamination incident in the aquifer as part of the city and county wellhead protection efforts.

The East Dakota Water Development District and the First District Association of Local Governments are developing a comprehensive ground water protection program in most of the Big Sioux aquifer area, including the coordination of wellhead protection programs in eleven counties. Known as the East Dakota Comprehensive Ground Water Protection Program, this effort includes standardizing county maps of aquifers, delineating wellhead protection areas, contingency planning, and public education in the eleven-county area. This effort also includes formulation of measures to reduce non-point source pollution of critical ground water areas and to change land uses that may be identified as having the potential to contaminate the ground water. The city of Sioux Falls and surrounding Minnehaha County have also developed and implemented wellhead protection measures for the Big Sioux aquifer. In addition, wellhead monitoring options are being researched and implemented in the Sioux Falls area. These efforts are already altering land-use practices over the aquifer. Experience with the Big Sioux aquifer shows that cooperation of State and local government, as well as input from the public, are essential for developing achievable and comprehensive ground water protection.

Other Sources of Information

State Contact:

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(605) 677-5227

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U.S. DEPARTMENT OF ENERGY

DOE Ground Water Resource Assessment at the Oak Ridge Reservation

This case study describes efforts by the Department of Energy's (DOE) Oak Ridge Reservation (ORR) to classify ground water in the vicinity of the ORR facilities consistent with Tennessee's Comprehensive Ground Water Management Program and in the context of DOE ground water protection program policy and requirements.

THE PURPOSE OF THIS RESOURCE ASSESSMENT

The purpose of this study was to conduct an assessment of the ground water resource at DOE's Oak Ridge Reservation in an effort to assist the State of Tennessee in completing its development of a ground water classification system and to help guide DOE ground water protection efforts at the Reservation.

Overview of DOE Ground Water Protection Program Requirements

Ground water protection at DOE sites nationwide is achieved by complying with applicable Federal and State regulations and with internal DOE orders. Order DOE 5400.1, entitled General Environmental Protection Program, establishes two basic ground water protection requirements for all DOE sites. One requirement is to develop and implement a Ground Water Monitoring Program to collect information on how DOE activities affect on-site and off-site environmental and natural resources. The second requirement is to develop and implement a site-wide Ground Water Protection Management Program to ensure that ground water remediation activities are coordinated and to establish systems to prevent future ground water contamination. Results of ground water monitoring activities are presented in an Annual Site Environmental Report, along with all other site environmental protection activities.

The Oak Ridge Reservation

ORR occupies 35,300 acres of Federally-owned land in eastern Tennessee. The site contains three major operating facilities: the Y-12 Plant, the K-25 Site, and the Oak Ridge National Laboratory (ORNL). The Y-12 Plant fabricates nuclear weapons components, processes nuclear materials, and provides technical support to other DOE facilities and laboratories. The K-25 Site had been involved in enrichment of uranium for use as a fuel in nuclear reactors prior to 1987, and is currently developing and demonstrating advanced enrichment technology and performing additional technical support. The ORNL is a multi-purpose research laboratory whose mission is to expand basic and applied knowledge in energy-related areas.

The geology of the ORR is typical of the Appalachian foreland fold and thrust belt. Lower Paleozoic sedimentary lithologies (shales and carbonates) are structurally repeated along regional thrust faults. From a hydrologic perspective, the ORR is underlain by alternating aquifer (carbonate) and aquitard (shale) units. The principal aquifer in the area is the Knox aquifer, which is composed of fractured dolomite and limestone. Although the Knox aquifer has not been fully evaluated, it appears that at the Y-12 plant, ground water may become saline (TDS >30,000 mg/L) below a depth of approximately 1,100 feet.

The depth of the vadose zone ranges from 45 to 90 feet from the surface. It is estimated that approximately 90 percent of the infiltration from the surface does not reach the water table, due to lateral migration along short flow paths to surface water, seeps, and springs.

To ensure that ground water resources are protected and to comply with applicable regulations and DOE Orders, ORR staff have developed a Ground Water Protection Management Program (GWPMP) for each of ORR's three major facilities. The GWPMP is a management tool designed to ensure that ground water activities are complete and comprehensive, and that lines of responsibility and communication mechanisms are established and functioning properly. Each facility has developed its own ground water monitoring program that is designed to identify existing ground water contamination, detect future contamination at the earliest possible point, and to ensure that standard methods for sampling, analysis, QA/QC, and reporting are used throughout ORR. Ground water coordinators at each ORR facility participate in a sitewide Ground Water Coordination Committee, which meets regularly to ensure consistency, exchange information, and report on the status of site investigations and technology evaluations.

Administration and Organization of Resource Assessment at ORR

It is DOE policy to comply with all applicable environmental statutes, regulations, and standards, and to incorporate national environmental protection goals into all DOE programs. DOE is committed to good environmental management at all of its facilities: to correct existing environmental problems, to minimize risk to public health and the environment, and to anticipate and address potential environmental problems before they pose a threat. In the course of carrying out DOE environmental protection policy, close coordination and interaction with State environmental agencies by each DOE site is strongly encouraged. An example of this coordination is provided by the ORR's efforts to classify ground water at ORR according to a classification system under development by Tennessee's Department of Environmental Conservation (TDEC). While ground water of drinking water quality is generally available throughout Tennessee, most residents in the vicinity of ORR receive their drinking water from a public water supply system that uses surface water. However, some rural residents rely upon private ground water wells.

Tennessee has begun to develop a Comprehensive Ground Water Protection Program that identifies Statewide goals, including developing a Statewide ground water data base, establishing formal coordination mechanisms with Federal, State, and local agencies, and classifying ground water resources throughout the State. Due to the complexity of the issue of ground water classification at the State level, TDEC is considering several alternative ground water classification schemes as part of the State's Ground Water Protection Program. Recently, the State has developed a preliminary classification system that would allow for differential management of ground water based on various ground water uses, with ground water that is of drinking water quality receiving the greatest protection.

A salient feature of the classification systems under consideration is the recognition of different levels of ground water protection for drinking water and other beneficial uses. According to a recently proposed classification scheme, TDEC could establish four ground water classes:

(1) current or potential drinking water supplies
(2) non-drinking water supplies, (i.e., water that is neither currently nor expected to be drinking water supplies but are protected for other purposes)
(3) ground water that may be used for the underground injection of fluids, as per State regulation
(4) ground water managed to assure the protection of the State's surface water, as per State regulation

The classification schemes currently under consideration reference water quality criteria for distinguishing ground water classes. For example, the Tennessee Primary Drinking Water Standards are used to classify drinking water supplies. In some cases, a ground water classification could be made following considerations of the yield of the well and whether the well water can be treated to meet State drinking water standards by conventional treatment methods.

At present, the State of Tennessee is reviewing various ground water classification options. To assist the State in completing development of its classification system, and to enable DOE to base ground water protection activities on the most complete and accurate understanding of subsurface conditions, DOE at Oak Ridge is implementing an approach that allows its staff to move forward with the development of a conceptual or preliminary framework for the classification of ground water at ORR, and to assemble a data base on subsurface conditions needed to perform preliminary classifications. The approach that the DOE at Oak Ridge is using has the following characteristics:

- Compatibility: The preliminary classification framework will be conservative and in general accord with the principles of Federal guidance on ground water classification (i.e., that the classification is protective of human health and the environment, and that the classification recognizes present and potential future use of the resource). When possible, DOE staff will strive to infuse the preliminary classification framework with timely and appropriate State input

- Utility: The activity of ground water classification will generate a data base that could provide technically useful information for on-going ground water protection activities

- Flexibility: The preliminary classification framework should serve as a basis for the implementation of Tennessee's classification, when Tennessee completes its Statewide system

ORR and the TDEC expect to rely on the system in the future to assist in making decisions regarding implementation of ground water protection program activities.

APPENDIX C:

Sources of Hydrogeological Information

Source: U.S. Environmental Protection Agency, 1992. RCRA Ground Water Monitoring: Draft Technical Guidance EPA/530-R-93-001 (NTIS # PB 93-139-350).

GENERAL DATA SOURCES

Source	Information Obtainable	Comments
Libraries	Earth science bibliographic indices	Many of the types of information discussed below can be obtained from libraries. Excellent library facilities are available at the U.S. Geological Survey offices (USGS) in Reston, VA; Denver, CO; and Menlo Park, CA. Local university libraries can contain good collections of earth science and related information and typically are repositories for Federal documents. In addition, local public libraries normally have information on the physical and historical characteristics of the surrounding area.
Computer literature searches	Bibliographic indices	Perhaps one of the most useful and cost effective developments in the bibliographic indexes has been the increased availability of computerized reference searches. On-line computer searches save significant time and money by giving rapid retrieval of citations of all listed articles on a given subject and eliminate manual searching of annual cumulated indexes. A search is done by use of keywords, author names, or title words, and can be delimited by ranges of dates or a given number of the most recent or oldest references. The average search requires about 15 minutes of online searching and costs about $50 for computer time and offline printing of citations and abstracts.
Dialog Subscriptions and information: 1-800-3-DIALOG.	Accesses over 425 data bases from a broad scope of disciplines including such data bases as GEOREF and GEOARCHIVE.	Provides indexes to book reviews and biographies; directories of companies, people, and associations; and access to the complete text of articles from many newspapers, journals, and other original sources.

Source	Information Obtainable	Comments
Master Directory (MD) User Support Office Suite 300 Hughes STX Corp. 7601 OraGlen Drive Greenbelt, MD 20771 (301) 513-1687 Span: BLAND NSSDCA. GSFC.NASA.GOV THIEMAN.NSSDCA. GSFC.NASA.GOV	The MD is a multidisciplinary data base that covers earth science (geology, oceanography, atmospheric science), space physics, solar physics, planetary science, and astronomy/astrophysics. It describes data generated by NASA, NOAA, USGS, DOE, EPA, and other agencies and universities, as well as international data bases.	MD is a free on-line data information service. Data available include personnel contact information, access procedures to other data bases, scientific campaigns or projects, and other data sources. Access Procedures: MD resides on a VAX at NSSDC and may be reached by several networks. MD is option #1 on the menu of NSSDC's On-line Data Information Services (NODIS) account. From span nodes: SET HOST NSSDA. USERNAME:NSSDC (no password). From Internet: TELNET NSSDCA.GSFC.NASA.GOV or TELNET 128.183.36.23.
Master Directory (continued)		Via Direct Dial: Set modem to 8 bits, no parity, 1 stop bit, 300,1200 (preferable), or 2400 baud. Dial (301) 286-9000 ENTER NUMBER: MD, CALL COMPLETE: [CR], USERNAME: NSSDC (no password). For assistance or more information, contact the MD User Support Office (301) 513-1687.

Source	Information Obtainable	Comments
Alternative Treatment Technology Information Center (ATTIC) 4 Research Place Suite 210 Rockville, MD 20850 (301) 670-6294 (voice) (301) 670-3808 (on-line)	The ATTIC system is a collection of hazardous waste databases that are accessed through a computerized bulletin board system (BBS). The BBS features news items, bulletins, and special interest conferences. ATTIC users can access several databases including the ATTIC Database, which contains over 2,500 records dealing with alternative and innovative technologies for hazardous waste treatment; and the RREL Treatability Database, which provides data on characteristics and treatability of a wide variety of contaminants. Information from these sources consists of treatability information, case histories, transport and fate data, and other technical information. Also included are the abstracts of Superfund Innovative Technology Evaluation (SITE) reports, many Records of Decisions (RODs), State agency reports, international programs, and industry studies.	ATTIC is free of charge to all members of the Federal, State and private sectors involved in site remediation. ATTIC can be accessed directly by a modem. Abstracts of reports can be downloaded from the system. Copies of complete reports are available on request. (Users register online the first time they access ATTIC.) A User's Manual is available and may be obtained by calling the ATTIC System Operator or leaving a message on the bulletin board.
Earth Science Data Directory USGS 801 National Center Reston, VA 22092 (703) 648-7112	ESDD is a data base that contains information related to the geologic, hydrologic, cartographic, and biological sciences.	Also included are data bases that reference geographic, sociologic, economic, and demographic information. Information comes from worldwide data sources and data includes that from NOAA, NSF, NASA, and EPA.

Source	Information Obtainable	Comments
Local, State, Federal, and Regional Agencies	Site specific assessment data for dams, harbors, river basin impoundments, and Federal highways, soils, land-use, flood plains, ground water, aerial photographs, well records, geophysical borehole logs	Many States maintain a department of the environment or natural resources. Reports can be obtained by contacting the responsible agency. Surface water and geological foundation conditions such as fracture orientation, permeability, faulting, rippability, and weathered profiles are particularly well covered in these investigations.
University sources	Engineering and geology theses	College and university geology theses, in most instances, are well-documented studies dealing with specific areas, generally prepared under the guidance of faculty members having expertise in the subject under investigation. Most theses are not published.
Comprehensive dissertation index	Doctoral dissertations	Citations began in 1861 and include almost every doctoral dissertation accepted in North America thereafter. The index is available at larger library reference desks and is organized into 32 subject volumes and 5 author volumes. Specific titles are located through title keywords or author names. Ph.D. dissertations from all U.S. universities are included.
AGI Directory of Geoscience Department	Faculty Members	Regular updates of faculty, specialties, and telephone date.
DATRIX II University Microfilms International 300 North Zeeb Rd. Ann Arbor, MI 48106 (800) 521-3042 ext. 732 (313) 761-4700 (in Alaska, Hawaii, and Michigan)	Dissertations and Masters theses	Using title keywords, a bibliography of relevant theses can be compiled and mailed to the user within two weeks. In addition, the DATRIX Alert system can automatically provide new bibliographic citations as they become available.

Source	Information Obtainable	Comments
United States Geology: A Dissertation Bibliography by State	Ph.D. dissertation or Masters theses	Free index from University Microfilms International. Some universities do not submit dissertations to University Microfilms for reproduction or abstracting, however, and the dissertations from these schools do not appear in the United States Geology index. Citations for dissertations not abstracted must be located through DATRIX II or Comprehensive Dissertation Index.
Dissertation Abstracts International, Volume B - Science and Engineering, a monthly publication of University Microfilm International	Extended abstracts of dissertations from more than 400 U.S. and Canadian universities	Once the citation for a specific dissertation has been obtained from the Comprehensive Dissertation Index or from DATRIX II, the abstract can be scanned to determine whether it is relevant to the project at hand. Since some universities do not participate, some theses indexed in the two sources listed above must be obtained directly from the author or the university at which the research was completed. Abstracts of Masters theses available from University Microfilms are summarized in 150-word abstracts in Masters Abstracts and are indexed by author and title keywords. Both Dissertation Abstracts International and Masters Abstracts are available at many university libraries. A hard (paper) or microform (microfilm or microfiche) copy of any dissertation or thesis abstracted can be purchased from University Microfilms.

Source	Information Obtainable	Comments
USGS Publication Manuscripts System (PUBMANUS) Earth Science Information Center 507 National Center Reston, VA 22092 (703) 648-6045	This data base provides referral to all U.S. Geological Survey publications.	Flexible searching techniques enable users to find information in numerous ways. Currently, search requests are accepted through the USGS Earth Science Publication Office at no charge. (800) USA-MAPS. The "Guide to Obtaining USGS Information" (circular 900) is also an excellent source. It describes the services provided by USGS information offices. Includes addresses and telephone numbers, and lists types of publications and information products and their sources. Publication is free and may be ordered from USGS Book and Report Sales. This guide can be obtained from USGS, Book and Report Sales, Box 25286, Denver, CO 80225, (303) 236-7477.
U.S. Geological Survey (USGS) Earth Science Information Center (ESIC) Reston, VA (703) 648-6045 1-800-USA-MAPS	Detailed topographic, geologic, and hydrologic information is available from the USGS through the Earth Science Information Center. United States historical, physical divisions, Federal-aid highways, national atlas and scientific maps.	ESIC can be contacted to determine which map best meets your needs. Maps can be purchased from: USGS Map Sales Box 25286 Denver, CO 80225 (303) 236-7477
Electric Power Research Institute (EPRI) ATTN: EPRI Technical Information Specialists 3412 Hillview Ave. Palo Alto, CA 94304 (415) 855-2411 (510) 934-4212 (distribution center)	Up-to-date compilation of research relevant to utilities.	The EPRI manages a research and development program on behalf of the U.S. electric power industry. Its mission is to apply advanced science and technology to the benefits of its members and their customers.

Source	Information Obtainable	Comments
RCRA/Superfund Hotline Office of Solid Waste (OS-305) U.S. EPA 401 M Street, SW Washington, DC 20460 (800) 424-9346 (toll free) (Washington, DC metropolitan area) (703) 920-9810	Information on RCRA, CERCLA, SARA, and UST statutes and corresponding regulations. Also provides document distribution service, including relevant Federal Register notices.	Team of information specialists maintains up-to-date information on the various regulations and rulemakings in progress. Hours of operation 8:30 a.m. to 7:30 p.m. (EST) Monday through Friday. Answer questions from wide range of callers - consultants, attorneys, generators, transporters, facility owner/operators, State and Federal regulatory agencies, trade associations, and the general public.

TOPOGRAPHIC DATA

Source	Information Obtainable	Comments
Branch of Distribution U.S. Geological Survey Maps Sales Box 25286, Federal Center Denver, CO 80225 (303) 236-7477	Index and quadrangle maps for the eastern U.S. and for States west of the Mississippi River, including Alaska, Hawaii, and Louisiana. Other scales are available.	A map should be ordered by name, series, and State. Mapping of an area is commonly available at two different scales. The quadrangle name is, in some instances, the same for both maps; where this occurs, it is especially important that the requestor specify the series designation, such as 7.5 minute (1:24,000), 15 minute (1:62,500), or two-degree (1:250,000).
Commercial map supply houses	Topographic and geologic maps.	Commercial map supply houses often have full State topographic inventories that may be out of print through national distribution centers.
Topographic Database National Geophysical Data at NOAA Code E/GCI 325 Broadway Boulder, CO 80303 (303) 497-6764	A variety of topography and terrain data sets available for use in geoscience applications.	The data were attained from U.S. government agencies, academic institutions, and private industries.
U.S. Geological Survey Topographic Map Names Database Attn. of Chief:GNIS USGS 523 National Center Reston, VA 22092 (703) 648-4544	This database contains descriptive information and official names for approximately 55,000 topographical maps prepared by the USGS, including out-of-print maps. Data includes the names of topographic maps, along with SE coordinates of the States in which they are located.	Printouts and searches are available on a cost recovery basis.

Source	Information Obtainable	Comments
U.S. Geodata Tapes Dept. of the Interior Room 2650 18th & C Sts., NW Washington, DC 20240 (202) 208-4047	These computer tapes contain cartographic data in digital form. They are available in two forms. The graphic form can be used to generate computer-plotted maps. The topologically-structured form is suitable for input to geographic information system for use in spatial analysis and geographic studies.	Tapes are available for the entire US, including Alaska, and Hawaii, and are sold in 4 thematic layers: boundaries, transportation, hydrography and US Public Land Survey System. Each of the four layers can be purchased individually. US Geodata tapes can be ordered through Earth Science Information (ESIC) Center, as well as through the following ESIC offices. Anchorage, AK - (907) 786-7011; Denver, CO - (303) 236-7477 and 7476; Menlo Park, CA - (415) 329-4309; Reston, VA - (703) 860-6045; Rolla, MO - (314) 341-0851; Salt Lake City, UT - (801) 524-5652; Spokane, WA - (509) 456-2524; and Stennis Space Center, MS - (601) 688-3541 or (601) 353-2524.
Geographic Information Retrieval and Analysis System (GIRAS) USGS Earth Science Information Center (ESIC) 507 National Center Reston, VA 22092 (800) USA-Maps (703) 648-6045	Land-use maps, land cover maps, and associated overlays for the United States.	These maps have been digitized, edited and incorporated into a digital data base. The data is available to the public in both graphic and digital form. Statistics derived from the data are available also. Users are able to search for either locations or attributes. To obtain information from this data base, contact ESIC.
Topographic Maps Users Service Geographic Names Information System (GNIS) Reston, VA 22092 (703) 648-7112	Organized and summarized information about cultural or physical geographic entities.	GNIS provides a rapid means of organizing and summarizing current information about cultural or physical geographic name entities. The data base contains a separate file for each State, the District of Columbia, and territories containing all 7.5-min. maps published or planned.
National Geophysical Data Center NOAA, Code E/GCI 325 Broadway Boulder, CO 80303 (303) 497-6764	This system contains a variety of topography and terrain data sets available for use in geoscience applications.	The data were obtained from U.S. Government agencies, academic institutions, and private industries. Data coverage is regional to worldwide; data collection methods encompass map digitization to satellite remote sensing.

GEOLOGIC DATA

Source	Information Obtainable	Comments
Geological Reference Sources: A Subject and Regional Bibliography of Publications and Maps in the Geological Sciences, Ward and others (1981)	Bibliographies of geologic information for each State in the U.S. and references general maps and ground water information for many sites.	Provides a useful starting place for many site assessments. A general section outlines various bibliographic and abstracting services, indexes and catalogs, and other sources of geologic references.
A Guide to Information Sources in Mining, Minerals, and Geosciences, Kaplan (1965)	Describes more than 1,000 organizations in 142 countries. Its listings include name, address, telephone number, cable address, purpose and function, year organized, organizational structure, membership categories, and publication format. Federal and State agencies are listed for the U.S. as well as private scientific organizations, institutes, and associations.	An older useful guide. Part II lists more than 600 worldwide publications and periodicals including indexing and abstracting services, bibliographies, dictionaries, handbooks, journals, source directories, and yearbooks in most fields of geosciences.
Bibliography and Index of Geology	Includes worldwide references and contains listings by author and subject.	This publication is issued monthly and cumulated annually by the American Geological Institute (AGI), and replaces separate indexes published by the U.S. Geological Survey through 1970 (North American references only) and the Geological Society of America until 1969 (references exclusive of North America only). Both publications merged in 1970 and were published by the Geological Society of America through 1978, when AGI continued its publication.
KWIC (Keyword-in-Contents) Index of Rock Mechanics Literature	Engineering geologic and geotechnical references.	The KWIC index is available in two volumes at many earth science libraries (Hoek, 1969; Jenkins and Brown, 1979).

Source	Information Obtainable	Comments
<u>GEODEX Retrieval System with Matching Geotechnical Abstracts</u> GEODEX International, Inc. P.O. Box 279 Sonoma, CA 95476	Engineering geological and geotechnical references.	The GEODEX is a hierarchically organized system providing easy access to the geotechnical literature and can be used at many university libraries. The GEODEX system can be purchased on a subscription basis.
U.S. Geological Survey Branch of Distribution 604 S. Pickett St. Alexandria, VA 22304	The U.S. Geological Survey (USGS) produces annually a large volume of information in many formats, including maps, reports, circulars, open-file reports, professional papers, bulletins, and many others.	To simplify the dissemination of this information, the USGS has issued a Circular (No. 777) entitled <u>A Guide to Obtaining Information from the USGS</u> (Clarke, et al., 1981).
U.S. Geological Survey Library Database USGS Main Library National Center MS 950 12201 Sunrise Valley Drive Reston, VA 22092 (703) 648-4302	The Reston library contains more than 800,000 monographs, serials, maps, and microforms covering chemistry, environmental studies, geology, geothermal energy, mineralogy, oceanography, paleontology, physics, planetary geology, remote sensing, soil science, cartography, water resources, and zoology.	This library system is one of the largest earth science libraries in the world. Library staff and users may access the online catalog from terminals at each of the 4 USGS libraries. The data base can be searched by author, title, key words, subjects, call numbers, and corporate/conference names. The general public is welcome to conduct literature searches using various data bases. Regional libraries are located in Denver, CO; Flagstaff, AZ; and Menlo Park, CA.
Geologic Names of the United States (GEONAMES) Geologic Division USGS 907 National Center Reston, VA 22092	GEONAMES is an annotated index of the formal nomenclature of geologic units of the United States. Data includes distribution, geologic age, USGS usage, lithology, thickness, type locality, and references.	Printouts are not available. Diskettes containing data for 2 or more adjacent States are available from USGS Open-File and Publications, Box 25425 Federal Center, Denver, CO 80225. Magnetic tapes can be obtained from NTIS.

Source	Information Obtainable	Comments
USDA Soil Conservation Service (SCS) (202) 720-1820	Soil maps and description are available for about 75% of the country through the U.S. Soil Conservation Service office located in each State capital.	

GEOPHYSICAL DATA

Source	Information Obtainable	Comments
U.S. Geological Survey Water Supply Papers	The most common types of geophysical data are available from seismic and resistivity surveys.	Water Supply Papers for an area can be located by any of the computer searches or published indexes described in the first section of this paper. In addition, the USGS also publishes geophysical maps of various types at relatively small scales for many areas of the U.S. Aeromagnetic maps have been completed for much of the U.S., although the flight altitude of several thousand meters and scale of 1:24,000 make these maps too general for most site specific work.
Well Log Libraries Electric Log Services P.O. Box 3150 Midland, TX 79702 Tel: (915) 682-7773	Electric logs for many petroleum wells can be obtained from one of several well log libraries in the U.S.	The geophysical logs are indexed by survey section. To obtain information on wells in a given area, it is necessary to compile a list of the townships, ranges, and section numbers covering the area.
Geophysical Survey Firms	Specific geophysical logs	Proprietary geophysical data can sometimes be obtained from private survey firms. In general, the original client must approve the exchange of information, and preference is given for academic purposes. If the information cannot be released, firms may be willing to provide references to published information they obtained before the survey, or information published as a result of the survey.

Source	Information Obtainable	Comments
NOAA National Geophysical Data Center (NGDC) Chief, Solid Earth Geophysics 325 Broadway Boulder, CO 80303 (303) 497-6521 Fax (303) 497-6513	NGDC maintains a computer database which contains information on earthquake occurrences from prehistoric times to the present. Historic U.S. earthquakes are included for the period starting in 1638. NGCD also maintains databases on other parameters, such as topography, magnetics, gravity, and other topics.	Site studies for many projects now require information regarding the seismicity of the region surrounding the site. The National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA) is a focal point for dissemination of earthquake data and information for both technical and general users, except for information on recent earthquakes. (Information about recent earthquakes can be obtained by contacting the USGS.) For a fee, a search can be made for one of the following parameters: - Geographic area (circular or rectangular area) - Time period (staring 1638 for U.S.) - Magnitude range - Date - Time - Depth - Intensity (Modified Mercalli)
Geomagnetism (GEOMAG) Branch of Global Seismology and Geomagnetism USGS Box 25046 Federal Center Mail Stop 968 Denver, CO 80225 (303) 273-8440 or (303) 273-8441	GEOMAG contains current and historical magnetic-declination information for the United States. It provides historical and current values of declination.	Current or historical values back to 1945 can be obtained over the telephone at no charge by calling (800) 358-2663. To access the full program via modem, contact the listed office for hook-up instructions. There is no subscription fee.

REMOTE SENSING

Source	Information Obtainable	Comments
USGS Earth Resources Observation Systems (EROS) Data Center User Service EROS Data Center U.S. Geological Survey Sioux Falls, SD 57198 (605) 594-6151	The EROS Program provides remotely-sensed data. To obtain publications, request further information, or place an order, contact the EROS Data Center.	The EROS Data Center, near Sioux Falls, South Dakota, is operated by the USGS to provide access primarily to NASA's Landsat imagery, aerial photography acquired by the U.S. Department of the Interior, and photography and multi-spectral imagery acquired by NASA from several satellite data systems sources. The primary functions of the Data Center are data storage and reproduction, user assistance, and training.
Landsat Data	Landsat satellites sensor images are found in spectral bands: - Band 4 (emphasizes sediment-laden and shallow water) - Band 5 (emphasizes cultural features) - Band 6 (emphasizes vegetation, land/water boundaries, and landforms) - Band 7 (as above, with best penetration of haze) - Band 5 gives the best general-purpose view of the earth's surface. Black and white images and false-color composites are available.	The Landsat satellites were designed to orbit the earth about 14 times each day at an altitude of 920 km, obtaining repetitive coverage every 18 days. The primary sensor aboard the satellites is a multi-spectral scanner that acquires parallelogram images 185 km per side in four spectral bands.

Source	Information Obtainable	Comments
EOSAT 4300 Forbes Blvd. Lanham, MD 20706 (301)552-0500	The Thematic Mapper provides data in 7 bands including one band of emitted infrared (thermal)	Thematic Mapper images are identical in scene size as LANDSAT MSS but have a 30 meter resolution. Repetitive coverage (revisit time) is reduced from 18 to 16 days. In addition, the detectors are placed directly at the focal planes of the optical system.
SPOT Image Corporation 1897 Preston White Dr. Reston, VA 22091 (703)620-2200	SPOT (Satellite Probatoire l'Observation de la Terre) is the European counterpart of LANDSAT. The data is essentially the same as that produced by LANDSAT.	SPOT gathers data in four spectral bands. Three bands are in 20 meter resolution and one is in 10 meter resolution. The system was designed to produce stereo pairs of images by pointing the detection system off-nadir (the ground area directly underneath the platform).
U.S. Department of Commerce NOAA/NEDIS/ NSDC Satellite Data Services Division (E/CCGI) World Weather Building, Rm 10 Washington, DC 20233	Advanced Very High Resolution Radiometer (AVHRR) is particularly useful for regional geologic analysis because of its wide scene size (2100 km). The data are collected in five spectral (including one thermal) bands at a resolution of 1100 meters.	The orbits are sun-synchronous (cross the same ground area repeatedly at the same local time). This line-scanning system sweeps through 56 degrees either side of nadir. This feature, together with an orbital altitude of 833 km produces the relatively large ground resolution. The ground resolution size distorts the image toward its edges and must be corrected geometrically by computer.
NASA Aerial Photography	Photography is available in a wide variety of formats from flight at altitudes ranging from one to 18 km. Photographs generally come as 230 mm by 230 mm prints at scales of 1:60,000 or 1:120,000, and are available as black and white, color, or false-color infrared prints.	NASA aerial photography is directed at testing a variety of remote-sensing instruments and techniques in aerial flights over certain preselected test sites over the continental U.S.

Source	Information Obtainable	Comments
Aerial Mapping Photography	Coverage obtained by USGS and other Federal agencies (other than SCS) available as 230 mm by 230 mm black and white prints taken at altitudes of 600 m to 12 km. Scales range from 1:20,000 to 1:60,000.	Because of the large number of individual photographs needed to show a region on the ground, photomosaic indexes are used to identify photographic coverage of a specific area. The Data Center has more than 50,000 such mosaics available for photographic selection.
Aerial Photography Field Office U.S. Department of Agriculture P.O. Box 30010 Salt Lake City, UT 84130 (801) 975-3503	Conventional aerial photography scales of 1:20,000 to 1:40,000.	Aerial photographs by the various agencies of the U.S. Department of Agriculture (Agricultural Stabilization and Conservation Service [ASCS], Soil Conservation Service [SCS], and Forest Service [USFS]) cover much of the U.S.
Photogrammetry Division of NOAA National Oceanic and Atmospheric Administration 6001 Executive Blvd. Rockville, MD 20852 (301) 443-8601 FTS 443-8601	The Coastal Mapping Division of NOAA maintains a file of color and black and white photographs of the tidal zone of the Atlantic, Gulf, and Pacific coasts. The scales of the photographs range from 1:20,000 to 1:60,000.	An index for the collection can be obtained by contacting the Coastal Mapping Division at (301) 443-8601 or the address listed.
U.S. Bureau of Land Management Aerial Photo Section Slyia Gorski (SC-67-C) P.O. Box 25047 Building 46 Denver, CO 80225-0047 (303) 236-7991	The Bureau of Land Management has aerial photographic coverage of over 50 percent of its lands in 11 western States.	For an index of the entire collection contact the U.S. Bureau of Land Management at (303) 236-7991 or the address listed.

Source	Information Obtainable	Comments
National Archives and Records Admin. Cartographic and Architectural Branch 8 Pennsylvania Ave., N.W. Washington, DC 20408 (703) 756-6700	Airphoto coverage from the late 1930's to the 1940's obtained for portions of the U.S. Also, foreign airphoto coverage for the World War II period is available.	This service may be important for early documentation of site activities.
National Air Photograph Library 615 Booth St. Ottawa, Ontario K1A 0E9 Canada (613) 995-4560 Fax (613) 995-4568		Canadian airphoto coverage can be obtained from the National Aerial Photograph Library at (613) 995-4560 or the address listed.
Canada Center for Remote Sensing 588 Booth Street Ottawa, Ontario K1A 0W7, Canada (613) 990-8033		Canadian satellite imagery can be obtained from the Canada Center for Remote Sensing at (613) 990-8033 or from the address listed.
Commercial Aerial Photo Firms American Society for Photogrammetry and Remote Sensing 5410 Grosvenor Lane Suite 210 Bethesda, MD 20814 (301) 493-0290		In many instances, these firms retain the negatives for photographs flown for a variety of clients and readily sell prints to any interested users. For a listing of nearby firms specializing in these services, consult the yellow pages.

HYDROLOGIC DATA

Source	Information Obtainable	Comments
Water Publications of State Agencies, Giefer and Todd (1972, 1976)	This book lists State agencies involved with research related to water and also lists all publications of these agencies. In general, hydrologic data can be classified into four primary categories: stream discharge, stream water quality, ground water level, and ground water quality.	The trend for the past decade has been to compile such basic data in computerized data banks, and a number of such information systems are now available for private and public users. Many data now collected by Federal and State water-related agencies are available through computer files, but most data collected by private consultants, local and county agencies, and well drilling contractors remain with the organization that gathered them.
Local Assistance Center of the National Water Data Exchange (NAWDEX) U.S. Geological Survey 421 National Ctr. Reston, VA 22092 (703) 648-5663	NAWDEX identifies organizations that collect water data, offices within these organizations from which the data may be obtained, alternate sources from which an organization's data may be obtained, the geographic areas in which an organization collects data, and the types of data collected. Information has been compiled for more than 1,700 organizations, and information on other organizations is added continually. More than 450,000 data collection sites are indexed.	NAWDEX, which began operation in 1976 and is administered by the U.S. Geological Survey consists of a computer directory system which locates sources of needed water data. The system helps to link data users to data collectors. For example, the NAWDEX Master Water Data Index can identify the sites at which water data are available in a geographic area, and the Water Data Sources Directory can then identify the names and addresses of organizations from which the data may be obtained. In addition, listings and summary counts of data, references to other water data systems, and bibliographic data services are available.

Source	Information Obtainable	Comments
WATSTORE Branch of Computer Technology USGS Reston, VA 22092 (703) 648-5686	WATSTORE maintains the storage of: 1) surface water, quality-of-water, and ground water data measured on a daily or a continuous basis; 2) annual peak values of stream flow stations; 3) chemical analyses for surface and ground water sites; 4) water-data parameters measured more frequently than daily; 5) geologic and inventory data for ground water sites; and 6) summary data on water-use.	Data can be retrieved in machine-readable form or as computer printed tables or graphs, statistical analyses, and digital plots. To retrieve WATSTORE data, contact: National Water Data Exchange (NAWDEX) Branch of Computer Technology USGS Mail Stop 421 Reston, VA 22092 (703) 648-5664
Published Water-Supply Studies and Data	Stream discharge, ground water level, and water quality data have been obtained during short-term, site-specific studies, and these data are typically available only in published or unpublished site reports. Data related to lakes, reservoirs, and wetlands are commonly found only in such reports.	Although significant progress has been made in computerizing surface- and ground water data, the majority remains available only through published and unpublished reports.
Catalog of Information on Water Data	The reference consists of four parts: - Part A: Stream flow and stage - Part B: Quality of surface water - Part C: Quality of ground water - Part D: Aerial investigations and miscellaneous activities.	Bibliographic publication indexes USGS sampling and measurement sites throughout the U.S. Maps are available that show a numeric code for each river basin and has information on drainage, culture, hydrography, and hydrologic boundaries for the 21 regions and 222 subregions designated by the Water Resources Council. Maps depict boundaries and codes of 352 accounting units within the National Water Data Network.

Source	Information Obtainable	Comments
Geologic and Water-Supply Reports and Maps (available for each State)		This publication lists references for each USGS division for each State or district, the listing, however, is by report number, requiring a scan of the entire list for information on a particular area.
Water Resources Investigations, by State Office of Water Data U.S. Geological Survey 417 National Ctr. 12201 Sunrise Valley Drive Reston, VA 22092	Listed are all agencies cooperating with the USGS in collecting water data, information on obtaining further information, and a selected list of references by both the USGS and cooperating agencies.	This booklet describes the projects and related publications for all current USGS work in a State or group of States. Also available is a useful summary folder with the same title that depicts hydrologic-data stations and hydrologic investigations in a district as of the date of publication. Additional assistance can be obtained by contacting: Hydrologic Information Unit, U.S. Geological Survey, 420 National Center, 12201 Sunrise Valley Drive, Reston, VA 22092.
Federal Flood Insurance Studies	To meet the provisions of the National Flood Insurance Act of 1968, the USGS, with funding by the Federal Insurance Administration, has mapped the 100-year floodplain of most municipal areas at a scale of 1:24,000.	Floodplain maps can be obtained from the nearest USGS district office and other agencies, such as the city, town, or county planning office, or the Federal Insurance Administration. Some areas have more detailed "Flood Insurance Studies" completed for the Federal Emergency Management Agency (FEMA); these include 100-year and 500-year floodplain maps. Complete studies are available at the nearest USGS office, city, town, or county planning office, or FEMA.
National Stream Quality Accounting Network (NASQAN) USGS Branch of Distribution 1200 South Ends St. Arlington, VA 22202	Regional and nationwide overview of the quality of our streams.	Consists of over 400 sampling sites. Data collection sties are located at or near the downstream end of hydrologic accounting units or at representative sites along coastal areas and Great Lakes.

Source	Information Obtainable	Comments
Office of Water Data Coordination (OWDC) USGS 417 National Center Reston, VA 22092 (703) 648-5016	Publications including the "National Handbook of Recommended Methods for Water-Data Acquisition," indexes to the "Catalog of Information on Water Data," and other publications.	OWDC is the focal point for inter-agency coordination of current and planned water-data acquisition activities of all Federal agencies and many non-Federal organizations.
National Ground Water Information Center (National Ground Water Association) 6375 Riverside Drive Dublin, OH 43017 (800) 332-2104 (614) 761-3446 (fax)	Computerized, on-line bibliographic database that provides a variety of information on the quantity and quality of ground water resources worldwide. Also includes references on such ground water topics as ground water protection, waste remediation, well design and construction, drilling methods, water treatment, and flow and contaminant transport models. Photocopying service of most database references and interlibrary loan service available. Public information brochures on ground water available.	Databases are accessible through computer, modem, and telecommunications software. Members and nonmembers can gain access. Abstracts are relatively short and nontechnical.

CLIMATIC DATA

Source	Information Obtainable	Comments
National Climatic Data Center (NCDC) Federal Building 37 Battery Park Ave. Asheville, NC 28801-2733 (704) 259-0682 or (703) 259-0871	Readily available are data from the monthly publication Climatological Data, which reports temperature and precipitation statistics for all monitoring stations in a given State or region. An annual summary is also available.	The National Climatic Data Center (NCDC) collects and catalogs nearly all U.S. weather records. Climatic data (which are essential for construction planning, environmental assessments, and conducting surface and ground water modeling) can be obtained from the NCC.
	In addition to collecting basic data, NCDC provides the following services: - Supply of publications, reference manuals, catalog of holdings, and data report atlases - Data and map reproduction in various forms - Analysis and preparation of statistical summaries - Evaluation of data records for specific analytical requirements - Library search for bibliographic references, abstracts, and documents - Referral to organizations holding requested information - Provision of general atmospheric sciences information.	NCC can provide data on file in hard (paper) copy, in microfiche, on magnetic tape, and on diskette. For general summary statistics and maps, the publication Climates of the States - NOAA Narrative Summaries, Tables, and Maps for Each State, by Gale Research Company (1980) is helpful.

APPENDIX D

Glossary

Adsorption - The attraction and adhesion of a layer of ions from an aqueous solution to the solid mineral surfaces with which it is in contact.

Advection - The process by which solutes are transported by the bulk motion of flowing ground water.

Aerial Photography - Photographs of the earth taken from either high or low altitudes and used to interpret natural and manmade surface features.

Aquifer - Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells or springs.

Aquifer Discharge Areas - An area of land where the zone of saturation is in direct contact with the ground surface. Discharging ground water may appear as springs, seeps, or as baseflow of streams.

Aquifer Recharge Areas - An area of land above or remote from an aquifer that allows infiltration of water to that aquifer.

Aquifer Test - Pumping of a well at a constant rate for a fixed period of time with concurrent water-level measurements in one or more nearby observation wells. The time-drawdown data are analyzed to yield quantitative aquifer parameter values.

Aquitard - A geologic unit of low permeability that can store and slowly transmit ground water from one aquifer to another. Aquitards act as confining units of aquifers.

Attenuation - The process by which a compound is reduced in concentration over time through one or more of the following processes: adsorption, degradation, dilution, or transformation.

Bail Piezometer Test - A single well test to determine the in-situ hydraulic conductivity of an aquifer by the instantaneous removal of a known quantity of water from a well, and the subsequent measurement of the recovery as a function of time.

Baseflow - That part of stream discharge that originates as ground water seeping into the stream.

Borehole Geophysical Logging - A general term that encompasses all techniques in which a sensing device is lowered into a borehole for the purpose of characterizing the associated geologic formations and their fluids. The results can be interpreted to determine lithology, geometry, resistivity, bulk density, porosity, permeability, and moisture content.

Bulk Density - The mass of dry soil including air space, per unit volume of material.

Chromatographic - Pertaining to a method for separating mixtures that makes use of the different tendencies that substances have for being adsorbed onto the surface of some stationary support.

Coefficient of Storage - See Storativity.

Confined Aquifer - An aquifer that is bounded above and below by low permeability formations or aquitards.

Cross-Section – A profile depicting the geologic materials and structures through a vertical slice of the earth.

Darcy's Law - An equation for the computation of the quantity of water flowing through porous media. Darcy's Law assumes that the flow is laminar and that inertia can be neglected. The law states that the rate of viscous flow of homogenous fluids through isotropic porous media is proportional to, and in the direction of, the hydraulic gradient.

Decay - The process by which a substance is broken down by either biotic or abiotic processes or through radioactive emission.

Degradation - The transformation over time of a compound into one or more similar chemicals.

Diffusion - The process by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

Dilution - To reduce the concentration of a component in a mixture by increasing the amount of one or more other components.

Dispersion - The spreading and mixing of chemical constituents in ground water caused by diffusion and mixing due to microscopic and macroscopic variations in velocities within and between pores.

Drawdown - The amount that a pumping well lowers the water table or potentiometric surface as water is removed. The amount of drawdown is a function of the discharge rate and the physical properties of the aquifer, such as hydraulic conductivity, storativity, and its boundaries.

Electrical Resistivity - Measurement of subsurface electrical resistance. Electrical resistivity is a function of the physical and mineralogical properties of soil and rock and the chemistry of pore fluids.

Electromagnetics - Method that measures subsurface conductivity through the use of low-frequency electromagnetic induction.

Equipotential - Lines of equal pressure; lines connecting points of equal hydraulic head.

Evaporation - The process by which water passes from the liquid to the vapor state. Water loss to the atmosphere (e.g., from surface water bodies, soil, etc.).

Evapotranspiration - Loss of water from the soil both by evaporation and by transpiration from the plants growing in the soil.

Fence Diagram - A projection of known stratigraphic columns to show the lateral thicknesses and interrelationships of geologic units.

Flow-Direction - The vector in which the water in an aquifer moves.

Flow-Net Analysis - Study to determine a set of interacting equipotential lines and flow lines representing a two-dimensional steady flow through porous media.

Gamma Logging - A borehole logging technique that measures the natural gamma radiation emitted by the formation rocks. It is used to delineate subsurface rock types, their positions, and thicknesses.

Geographic Information System (GIS) - A computerized data base/mapping system that may be used to store, retrieve, and analyze information, such as soil and hydrogeologic data, based on geographic location.

Geologic Cross-Section - Method of extrapolating surface geologic observations to the relationships of geologic units under the surface. A cross-section is a two-dimensional presentation of a study area and can be either of large or small scale.

Geologic Structure - The form, symmetry, and geometry of geologic units. Structural geology may include the study of folds, faults, and joints, as well as the mechanical properties of rocks.

Geophysical Methods - Means of obtaining data on subsurface conditions. Includes use of electromagnetics, ground-penetrating radar, electrical resistivity, magnetics, seismic refraction and reflection, gravity, and borehole measuring techniques.

Ground-Penetrating Radar (GPR) - A surface geophysical technique based upon the transmission of repetitive pulses of electromagnetic waves into the ground. Some of the radiated energy is reflected back to the surface and the reflected signal is captured and processed. GPR is useful for defining the boundaries of buried trenches and other subsurface installations.

Ground Water Withdrawal - Removal of water from an aquifer by pumping.

Half-Life - The time required for a pollutant to be reduced by 50 percent of its original amount.

Hydraulic Conductivity - A coefficient of proportionality that describes the rate at which a fluid can move through a permeable medium. It is a function of both the media and of the fluid flowing through it.

Hydraulic Gradient - A measure of the change in ground water head over a given distance.

Hydraulic Head - The height above a specific datum (generally mean sea level) that water will rise in a well.

Hydrogeologic Setting - The composite description of the regional geology of a specific area that characterizes the stratigraphy, structure, and lithology of the materials, and the occurrence and chemistry of the ground water.

Hydrograph - A graph that shows the elevation of ground water in a well, or surface water level, above a particular datum point, against time.

Hydrologic Cycle - The endless circulation of water between the ocean, atmosphere (by evaporation), land (by precipitation), and back to the ocean (by stream and subsurface flow).

Hydrology - The study of the occurrence, distribution, circulation, and chemistry of water.

Impermeable Strata - Layers of rock or sediment that do not allow the transmission of water.

Infiltration Test - Field or lab tests used to measure the permeability or hydraulic conductivity of a porous media as a liquid passes through it. These tests are usually used to analyze a soil profile.

Interflow - The lateral movement of water in the unsaturated zone during and immediately after a precipitation event. The water moving as interflow discharges directly into a stream or lake.

Intrusive Borehole Tests - Techniques that measure resistivity, conductivity, radioactive properties, velocity, density and other physical properties, depending on the tool used. The specific borehole tools are lowered downhole and the data are recorded continuously either digitally and/or by hard copy.

Isopach Map - A map showing areas of an aquifer or geologic formation of the same thickness.

Isotropy - The condition in which the property or properties of interest are the same when measured along axes in any direction.

Karst - Areas underlain by soluble bedrock (e.g., limestone, dolomite) that are generally characterized by surface and subsurface features (e.g., sinkholes, caves) formed by the dissolution of rock by ground and surface water. These landscapes can describe an area containing specific solutionally-modified landforms as well as well as areas underlain by solutionally-derived conduit aquifer systems.

Leaky Aquifer - A low-permeability layer that can transmit water at sufficient rates to furnish some recharge to a well pumping from an adjacent aquifer.

Lithologic Correlation - Verifying results of an analytic method through direct study of the macroscopic features of a rock (e.g., its texture or petrology).

Macropores - Spaces within a geologic material above the water table that are too large to hold water by capillary action. Macroporosity may result in enhanced migration of contaminants into ground water.

Organic Matter - The material of a living organism and/or the remains or a key byproduct of a living organism.

Particle Density - The mass per unit volume of soil particles, usually expressed in grams per cubic centimeter.

Partition Co-Efficient - The ratio of concentration of a chemical sorbed to the solid phase to its concentration in the aqueous phase (Kd).

Permeability - The ability of a porous medium to transmit fluids under a hydraulic gradient. Highly permeable soils are more likely to result in the leaching of contaminants than soils of lower permeability.

pH - A measure of the acidity or alkalinity of a liquid or solid material.

Piezometer - Generally a small-diameter, non-pumping well used to measure the elevation of the water table or potentiometric surface.

Plume - The area of a measurable discharge of a contaminant from a given point of origin.

Porosity - The ratio of the volume of small openings in soil or rock to its total volume, usually expressed as a percentage.

Potentiometric Surface - A surface that represents the total head of ground water in a confined aquifer that is defined by the level to which water will rise in a well.

Redox - A chemical reaction in which an atom or molecule loses electrons to another atom or molecule. Also called oxidation-reduction. Oxidation is the loss of electrons; reduction is the gain in electrons.

Retardation - Preferential retention of contaminant movement in the subsurface zone. Retention may be the result of adsorption processes or solubility differences.

Runoff - The total amount of water flowing into a body of water. It includes overland flow, return flow, and interflow.

Salt Water Encroachment - The movement, as a result of human activity, of saline ground water into an aquifer formerly occupied by fresh water. Passive saline water encroachment occurs at a slow rate owing to a general lowering of the fresh water potentiometric surface. Active saline water encroachment proceeds at a more rapid rate owing to the lowering of the fresh water potentiometric surface below sea level.

Satellite Imagery - Images that are produced from the reflected electromagnetic radiation as recorded by satellites. These images are used to identify and assess cultural, geographic, climatic, and geologic features of the earth.

Saturated Zone - The subsurface zone where pore spaces are completely filled with water.

Seepage Meter - A device used to measure leakage from underlying aquifers into stream beds or through emergence of ground water into a stream channel.

Seismic Methods - Exploration of subsurface geologic structures by means of seismic waves that are induced at the surface.

Slug Piezometer Test - A single well test to determine the in-situ hydraulic conductivity of an aquifer by the instantaneous addition of a known quantity (i.e., slug) of water into a well, and the subsequent measurement of the resulting recovery time.

Soil - The natural, weathered, unconsolidated, mineral and organic matter on the surface of the earth; it is a medium for the growth of plants.

Specific Retention - The ratio of the volume of water that a given body of rock or soil will hold against the pull of gravity to the volume of the body itself. It is usually expressed as a percentage.

Specific Yield - The ratio of the water drained from a rock under the influence of gravity, or removed by pumping, to the total volume of the rock voids or pore space in the drained rock.

Stack-Unit Maps - A map showing the areal distribution of geological materials based on their order of occurrence to a specified depth.

Stiff Diagram - A graphical means of presenting the chemical analysis of the major cations and anions of a water sample.

Storativity (Coefficient of Storage) - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In unconfined aquifers it is equal to the specific yield, but in confined aquifers, the storage coefficient depends on elastic compression of the aquifer and is usually less than 10^{-3}.

Subsidence - Sinking or settling of the ground surface due to natural or anthropogenic causes. Surface material is displaced vertically downwards with little or no horizontal movement. One anthropogenic cause of subsidence is ground water pumpage from unconsolidated aquifers that greatly exceeds the recharge rate and depletes the aquifer.

Temporal Variations - Some characteristics of ground water vary depending upon the time of year. For example, water levels in shallow aquifers in the Eastern United States for the summer and winter months will be lower than levels in the spring and fall when most of the yearly precipitation occurs. Ground water managers need to be aware of these variations when assessing ground water.

Topography - The physical features of a surface area including relative elevations and the position of natural and manmade features.

Total Organic Carbon - The amount of carbon existing as part of organic compounds in a sample. Excludes inorganic forms of carbon such as CO_2 and $CaCO_3$.

Tracer Tests - Tests that measure the reduction over time of the concentration of a tracer as well as the arrival times of ground water flow at a known point. Possible tracers include salt, radioactive isotopes, and fluorescent dyes.

Transformation - The physical, chemical, and biological processes by which a molecule of a chemical is altered to form a higher- or lower-molecular-weight chemical.

Transmissivity - The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of the properties of the liquid, the porous media, and the thickness of the porous media.

Trilinear Diagram - A method of graphically plotting the chemical composition of the major anions and cations of a water sample.

Unconfined Aquifer - An aquifer characterized by the absence of an aquitard above it, so that the water table forms the upper boundary of the aquifer and is free to move with atmospheric influences such as atmospheric pressure. Also referred to as a water table aquifer.

Vadose Zone - The subsurface zone where pore spaces are not completely filled with water.

Volatile Organic Compound - Any organic compound that participates in atmospheric photochemical reactions except for those designated by the EPA Administrator as having negligible photochemical reactivity.

Water Budget - A method of assessing the size of future water resources in an aquifer, catchment area, or geographical region that involves evaluating all the sources of supply or recharge in comparison to all known discharges or abstractions.

Water Table - The level below which the soil or rock is saturated with water. It is also the upper boundary of the saturated zone. At this level, the hydraulic pressure is equal to atmospheric pressure. Also used to refer to an aquifer that exists in unconfined conditions (e.g., a water table aquifer).